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ENVIRONMENTAL PLANNING MANUAL
FOR
SALINITY MANAGEMENT IN IRRIGATED AGRICULTURE

by

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FOREWORD

The Environmental Protection Agency was established to coordinate administration of the major Federal programs designed to protect the quality of our environment.

An important part of the Agency's effort involves the search for information about environmental problems, management techniques, and new technologies through which optimum use of the Nation's land and water resources can be assured and the threat pollution poses to the welfare of the American people can be minimized.

EPA's Office of Research and Development conducts this search through a nationwide network of research facilities.

As one of these facilities, the Robert S. Kerr Environmental Research Laboratory is responsible for the management of programs to: (a) investigate the nature, transport, fate and management of pollutants in groundwater; (b) develop and demonstrate methods for treating wastewaters with soil and other natural systems; (c) develop and demonstrate pollution control technologies for irrigation return flows; (d) develop and demonstrate pollution control technologies for animal production wastes; (e) develop and demonstrate technologies to prevent, control or abate pollution from the petroleum refining and petrochemical industries; and (f) develop and demonstrate technologies to manage pollution resulting from combinations of industrial wastewaters or industrial/municipal wastewaters.

This report contributes to the knowledge essential if the EPA is to meet the requirements of environmental laws that it establish and enforce pollution control standards which are reasonable, cost effective and provide adequate protection for the American public.

William C Galegar
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Director
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PREFACE

No other natural resource in the United States may be subjected to as many legal, socio-economic and institutional arrangements as water. There are federal, state, and local laws, policies, and administrative regulations. In addition, there is an abundance of small water districts, natural resource districts, groundwater districts, and many other special districts each with its own priorities, programs, regulations, responsibilities, and areas of jurisdiction. These institutions are often in direct conflict with one another; moreover, if one represents agricultural uses and others represent industrial and municipal uses, conflicts are frequently solved via the legal system which may take several years.

A governmental restriction that ties these diverse institutions together is the national water quality program, PL 92-500, Section 208. Administration and implementation of the Section 208 programs is a difficult task since plans must be formulated for regional water quality goals that are compatible with all users. The most difficult area of water use to accurately assess and formulate workable pollution control programs is agricultural water use. The agricultural assessment is complicated by its diffuse nature and the pollution potential from pesticides, fertilizers, sediment, and salinity. To compound the problem, each type of pollution or combination of pollutants has a unique "site-specific" set of solutions for each agricultural area. The pollution potential of salinity in irrigated agriculture is an area of major national and international concern.

The EPA research and development program regarding irrigation return flow quality control has made substantial progress in the past several years. Considerable effort has been given to salinity problems and their control in irrigation return flows with more and more attention being devoted to identifying processes for implementing both technological (hardware) and institutional (software) measures for reducing salt loads from irrigated agriculture. This manual is an attempt to compile these research results in such a manner that they can be used by action organizations responsible for implementing, managing, and controlling water pollution from irrigated agriculture.

Gaylord V. Skogerboe
Wynn R. Walker
Robert G. Evans

ABSTRACT

An environmental planning manual for salinity management in irrigated agriculture has been prepared. The primary focus of this manual is a delineation of the combinations of technological and institutional solutions, the various levels of planning effort, use of existing data and necessary field investigations which are required for the different planning levels, methods of data analysis, technological and socio-economic considerations in implementing a salinity control program, and finally, recommendations for formulating an action program.

It is intended that the primary audience for this manual would be environmental planners such as EPA Regional Offices, state water pollution control agencies, regional councils of governments, and 208 (Section 208 of PL 92-500) planning groups. In addition, it is intended to serve as a guide to be used and tailored at the discretion and guidance of the supervisory personnel to persons without prior training or experience in assessing the nonpoint source pollution problems of irrigation return flows due to salinity.

This report was submitted in fulfillment of Grant No. R804672 to Colorado State University, under sponsorship of the U.S. Environmental Protection Agency. This report covers the period of August 22, 1976 to August 31, 1978, and work was completed as of August 31, 1978.

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LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

ac --acre, (43,560 ft^2) one acre equals 0.4046 hectare
AF --acre-foot, volume of water to cover one acre a depth of one foot, one Acre-foot equals 0.1233 hectare-meters
BTU --British Thermal Unit
cal/gm --calories per gram
cfd --cubic feet per day
cfs --cubic feet per second, volume flow rate of water, one cfs equals 0.0283 cubic meter per second
cmd --cubic meter per day
CMI --Colorado Miner's Inch, one Colorado Miner's Inch equals 0.74 liters per second
degrees C or °C --Centigrade temperature (also called Celsius) scale
degrees F or °F --Fahrenheit temperature scale
ft --feet, unit of length, one foot equals 0.3048 meters
gm --gram, 454 grams equal one pound
gpm --gallons per minute, volume flow rate of water, one gallon per minute equals 0.0631 liters per second
ha --hectare, metric unit of area, one hectare equals 2.471 acres
ha-m --hectare-meter, volume of water to cover one hectare to a depth of one meter, one ha-m equals 8.108 AF
hr --hour, 60 minutes
hp --horsepower, one horsepower equals 7.460 x 10^{-5} erg/sec
in --inch, one inch equals 2.54 centimeters
km --kilometer, metric unit of length, one kilometer equals 0.621 mile
lb --pound (mass)
l/s --liters per second, volume flow rate of water
m --meter
m^3/s --cubic meters per second, volume flow rate of water

me/l	--milliequivalents per liter
mg/l	--milligrams per liter, equal to one ppm
mi	--mile, one mile equals 1.609 kilometers

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Finally, the efforts and advice given by the EPA Project Officer, Dr. James P. Law, Jr., have been extremely helpful in the successful pursuit of this project. He has generously given of his time to cooperatively achieve the goals of the project.

SECTION 1

PLANNING FRAMEWORK

The increasing complexity of assessing the physical, economic, legal, sociological, and institutional aspects of irrigated agriculture has necessitated the development of extensive resource materials. The need for current and detailed information on salinity management in irrigated agriculture along with specially trained personnel has been acknowledged by staffs involved in regional water quality management. Recently, numerous research projects regarding irrigation return flow quality control have been completed. It is highly desirable that these research results be disseminated for use by action organizations responsible for implementing, managing, and controlling water pollution from irrigated agriculture.

This manual has been developed to provide a basis for the determination of the significance of salinity problems, delineation of the combinations of technological and institutional solutions, determination of the various levels of planning, evaluation of field investigations required for the different planning levels, and selection of methods for data analysis. Ultimately, these areas lead to a planning framework for the implementation of action programs.

PURPOSE OF THE MANUAL

This manual is designed to assist areawide administrators responsible for nonpoint source agricultural salinity control programs under the jurisdiction of the Federal Water Pollution Control Act of 1972 (Public Law 92-500) and the Clean Water Act of 1977 (PL 95-217). Congressional mandates have specified that regional investigations, commonly referred to as Section 208 studies, be undertaken to identify significant nonpoint sources of pollution, to develop plans for the control of these pollutants, and to design programs for the implementation of these pollution abatement plans. The legal basis for requiring these studies is detailed in Section 201(c) and Sections 208(b)(2)(C)(F) through (K) of P.L. 92-500.

This manual is to provide administrators working under the regulations of Section 208 a basis to judge the adequacy of technical studies contracted under their supervision. Environmental planners, state water pollution control agencies, regional councils of governments, agriculturalists, environmentalists, consulting engineers, and action agency personnel can also be assisted by this manual. Generally, information presented in the manual serves as a guide and reference source for any person actively engaged in the analyses and development of best management practices for irrigated agriculture. This report provides an interdisciplinary framework for (a) identifying salinity pollution problems in agriculture; (b) developing the best management practices for salinity control; and (c) implementing best management practices.

SCOPE

It should be noted this manual does not specifically recommend or present descriptions of the advantages and disadvantages of various investigative techniques for salinity control since the volume of material would be overwhelming. It does, however, stress the need for an interdisciplinary approach for studying salinity which is necessary when viewing the physical complexity of the soil-water-plant regimes, the socio-economic and political implications of water, and the rapid expansion of irrigated agriculture throughout the United States. Throughout the text it is emphasized that there are no set values for the various parameters and specific solutions that universally apply to the salinity control problems of irrigated agriculture. Instead, this report presents a rational framework by which any irrigated area suspected of contributing significant amounts of nonpoint source pollution can be evaluated.

Generally, this report is concerned with gravity diversion irrigation delivery systems which are common in the western United States. On the other hand, due to power costs and other economic considerations which reflect the true cost of water, pumped groundwater systems are usually operating at higher irrigation water use efficiencies and alternatives for improved water management are often limited. Rawlins (1976) discusses some alternatives which can be considered for extensive groundwater use areas.

Procedures and methods for evaluating surface return flow problems with sediment and biocides and groundwater nitrate pollution are beyond the scope of this manual, but these subjects are adequately addressed by Evans and Duseja (1973), Dornbush et al., (1974), McNeal and Carlile (1976), Pratt (1972), Carter and Bondurant (1976), and Wendt et al., (1976). It should be noted that many of the investigative procedures and some potential solutions discussed in this manual for salinity control apply also to the control of other types of nonpoint source pollution. Additional information on water quality management problems due to irrigated agriculture can be found in Law and Witherow (1970), and King and Hanks (1975).

MEETING NATIONAL GOALS

There are several national goals that impinge on the subject of salinity management in irrigated agriculture. Besides reducing water pollution in order to have cleaner water, it is also necessary to continually increase crop production, to provide water to meet new water demands by agriculture, municipalities and industries, and to reduce energy consumption.

The forecasted increase in irrigated acreage will result in higher pollution potentials from agriculture throughout the United States. Therefore it should be expected that control of pollution from irrigation return flows and other agricultural sources in all areas of the country will receive more and more emphasis in the future.

Improved irrigation water management practices will not only reduce pollution from irrigated agriculture, but will also increase crop production, reduce energy consumption and increase water supplies available for new demands of other beneficial uses. The necessity for pollution control programs and the concomitant benefits to other national goals will continue to direct more and more attention to the control of irrigation return flows. Consequently, more agricultural areas will need to be evaluated and questions regarding the quantity and quality of the irrigation return flows will need to be answered.

Because many of the nonpoint pollution parameters tend to be site-specific, every area should be evaluated individually. The same conditions encountered in one area may result in an entirely different set of consequences in another area. The conditions in areas such as the Grand Valley of Colorado are not necessarily the same in the Imperial Valley of California, Wellton-Mohawk Project of Arizona, Platte River of Colorado, Wyoming and Nebraska, Snake River of Idaho, Oregon and Washington, or the Red River of North Dakota. To assume nonsite-specific "representative" value implies that decisions can be made without technical information with a reasonable probability of success. This is clearly not the case, and very often the components of a nonpoint source pollution control program are not intuitive.

Mineral pollution is the most serious water quality problem in many areas of the United States, most notably in the Colorado River Basin. The problem is serious because the Basin is approaching conditions of full development and utilization of the available water resources. While the salinity problem may seem unique to basins of the arid West, it will ultimately be faced by nonarid areas as water use approaches the available supply.

The United States Environmental Protection Agency (1971) reported that existing damages due to salinity to Lower Colorado River Basin users would increase from $16 million annually in 1970 to $51 million annually by the turn of the century, if planned developments do not include appropriate salinity control measures. More recent estimates by the United States Bureau of Reclamation (Bessler and Maletic, 1975) show present damages at $53 million annually, which is projected to be $124 million annually by the year 2000. Irrigated agriculture accountsonly for 37 percent of the total salt load of the Colorado River at Imperial Dam.

The Upper Colorado River Basin water users are particularly affected by these conditions because most of the future developments involve trans-basins diversions, in-basin oil shale development, and possible hydroelectric and thermoelectric production. None of these water uses add significantly to the salt loading aspect, but each diminishes the quantity of water available for diluting the salt loads already being carried. Future development of water resources in the Upper Colorado River Basin must be associated with more rigid salinity controls on the existing salt sources, many of which are related to agricultural water uses.

IDENTIFICATION OF SALINITY PROBLEMS

Salinity includes inorganic chemical salts of sodium, magnesium, potassium, and calcium that form bicarbonates, carbonates, chlorides, sulfates and nitrates which are dissolved in water or are present in soil. It is a naturally occurring pollutant that is always carried by the rivers or streams in varying concentrations. Salinity control is a controversial subject that illustrates only one of the many aspects of the quality-quantity conflicts that occur in water short areas. It is necessary to derive a salinity control program that balances water quality and water quantity with in-stream and off-stream beneficial uses such as fisheries and recreation with irrigation and industrial uses. It is hoped that this manual will provide insight to developing realistic as well as acceptable nonpoint source pollution control programs that can be implemented. It is necessary that the solutions be acceptable to the irrigators, environmentalists, and regulating agencies.

In studying salinity problems of an irrigated area, the first step is to determine the impact of the resulting pollution. This may be accomplished by an inflow-outflow analysis which essentially analyzes the quantities of water and salt entering and leaving an irrigated area. If the subsurface irrigation return flows pass through the groundwater reservoir and then return to the river, an inflow-outflow analysis can be performed using gaging stations upstream and downstream from the irrigated area. However, if the groundwater level is deep, which usually is the result of heavy pumping, the outflow must be measured in the groundwater reservoir, where increasing salinity concentrations of the presence of nitrates alone could indicate pollution of the groundwater reservoir.

The important question is whether certain uses of the water downstream are impaired as a result of the increased salinity concentrations. If the groundwater reservoir is being polluted, then it would be important to evaluate the continued use of groundwater supplies. For instance, if nitrate concentrations in the groundwater were increasing with time, it would be important to know whether the water is suitable for present and future domestic use.

The existence of salinity problems in the irrigated area is also of environmental concern. Irrigation water supplies having high salinity concentrations, or more likely, high groundwater levels resulting from excessive water use, poor natural drainage, or a combination of factors, are likely to create significant environmental changes such as permitting development of different plant and animal species.

Once a salinity problem is recognized in an irrigated area, a more difficult problem becomes the identification of the sources of the problem. The first question to be resolved is how much of the salt pollution results from irrigated agriculture, municipalities and industries, or natural sources such as runoff from precipitation and snowmelt. Typically, these questions are difficult to answer and require considerable analysis. The required approach is to prepare water and salt budgets for the area by developing a hydro-salinity model as described in Section 6. The sources of salinity from irrigated agriculture are the result of seepage losses from canals and laterals, as well as deep percolation losses from overirrigation of croplands. Therefore, it becomes necessary to measure seepage and deep percolation losses throughout the irrigated area. Field procedures for measuring these losses are discussed in Section 8.

For most areas, a reduction in seepage and deep percolation losses will not result in a corresponding decrease in the volume of salts leaving the area. For such situations, it is necessary to evaluate the chemical changes in the subsurface return flows as they move through the soil profile and are transported through the groundwater reservoir. Such an analysis involves soil moisture-chemistry simulation, which is described in Section 7.

Basic Considerations

Irrigated agriculture is not always the major contributor to the salinity problem in an area. For example, in the Upper Colorado River Basin, natural runoff and natural point sources contribute more than 60 percent of the total salt load, and irrigated agriculture contributes about 37 percent. The salinity concentrations from irrigated agriculture are usually much higher, the areal extent is much smaller, and efficient and cost-effective control is easier to attain.

Irrigation has two primary objectives: (a) to supply the essential moisture for plant growth; and (b) to leach or dilute the chemical salts in the applied water and in the soil. The first objective of supplying the necessary moisture can be accomplished in several ways. Regardless of the method used, the purpose of irrigation is to periodically replenish the soil moisture depleted by the consumptive demands of the plant.

The second objective of irrigation is very important and will often occur naturally during an irrigation as deep percolation. In fact, if these salts are not periodically flushed or leached from the crop root zone, the land will become nonproductive in a relatively short time. It is also this second objective of irrigation that is responsible for the salinity problems in irrigation return flows. Sustained agriculture must have a certain amount of salinity in its return flows.

DEVELOPMENT OF BEST MANAGEMENT PRACTICES

Once the magnitude of the subsurface irrigation return flows are quantified, it becomes possible to identify appropriate technologies for alleviating water quality degradation. The first step is to move from the potential solutions described in Section 4 to solutions that are appropriate to the particular area under study.

Those solutions identified as appropriate should be tested on farmers' fields in order to develop alternatives that are acceptable to farmers. At the same time, the soil moisture-chemistry simulation should be undertaken so quality and quantity impacts of reducing subsurface irrigation return flows being transported ultimately to the stream can be evaluated. This process of shifting from *potential solutions* to *appropriate solutions* to developing *acceptable solutions* is very important if a salinity control program is to be developed which can be implemented successfully.

Appropriate solutions must also consider the institutional constraints, such as the existing water law and water rights systems. For example, a tailwater reuse system may not be a best management practice to be implemented in some areas if the reduced irrigation return flows interfere with downstream water rights. Also, evaporation and disposal of saline waters may deprive another appropriator of his water right, regardless of how saline that water may be.

The cost-effectiveness of a particular technology is defined herein as the cost of implementing the technology versus its effectiveness in reducing the salt load in the groundwater reservoir or river, as well as the concern for reclaiming unproductive salinized soils. The cost-effectiveness of each appropriate technology must be developed for the "site-specific" case under study to arrive at an optimal mix of technologies that will alleviate the salinity problems. The best management practices will be those technologies that will also be acceptable to the farmers. The solutions must be acceptable to the irrigator, since it is his management of the system that will maximize the potential of the improved irrigation practices. Mandated efficiencies are very difficult to enforce without a commitment from the irrigator-farm manager. This is discussed in more detail in Sections 9 and 10.

River Basin Salinity Planning

The majority of Section 208 planning efforts are directed towards identifying measures required to control salinity in individually irrigated areas or subbasins. However, plans must also be developed for the entire river basin in order to determine the level of the programs to be implemented. It is important to understand that salinity planning involves three steps. First, evaluation of alternatives for each area leads to management practices that can effectively control salinity from use of irrigation water. These plans should indicate optimal policies for reducing salinity by amounts ranging from the maximum potential control achievable to no control as prescribed by each specific area.

There are several ways that the salinity control policies, program costs, and the resulting effectiveness of a program can be evaluated. One method is a cost-effectiveness technique which relates the implementation cost to the corresponding net unit reduction in salt loading for the salinity control measures. The cost-effectiveness method is used in this report. A total benefit approach can also be used which considers local benefits such as increased crop production, aesthetics, and reclamation of saline loads, as well as the reduction in downstream salinity damages. In some cases, only the potential downstream benefits of a salinity control project are used for program comparisons. The subarea analysis is illustrated in Figure 1.

In each subarea, the magnitude of the problem must be determined and the sources delineated. This should include the magnitude of subsurface irrigation return flows resulting from seepage losses and deep percolation losses, along with changes in chemical composition of these flows enroute to the groundwater reservoir and, subsequently, the river. When this is accomplished, the best management practices must be developed to alleviate the salinity problems. Appropriate solutions should be demonstrated and evaluated on farmers' fields to develop alternatives that are acceptable to both the farmers and various regulatory agencies. In addition, cost-effectiveness analysis must be applied to the acceptable solutions to arrive at best management practices. Finally, the basis for implementation of the best management practices must be established.

The second step in establishing the most cost-effective salinity control program is to define the best management practices by optimizing cost-effectiveness relationships from individual areas into a single strategy. This planning function delineates the level of salinity control required in each individual subbasin to achieve the overall goal for water quality improvement with the least cost. Relative levels of implementation among the areas are also determined.

The third step assigns the required level of salinity control that should be implemented in each subbasin or irrigated area. The basin planning process for salinity control involves integration of planning studies at the local level into the total basin framework to define the best management practices on a basin-wide scale. By integrating the results outlined in the first step, the best management practices for salinity control in each area are identified. A summary of this process is shown schematically in Figure 2.

If it is not possible or feasible to determine a basin-wide salinity control program, the processes involved in alleviating salt pollution from an individual area must be determined as shown in Figure 3. This analysis is identical to the process outlined in the first step, but the scale is much smaller and the best management practices are tailored to the subarea.

Finally, best management practices should include educational programs, technical assistance programs, improved water delivery systems, and improved irrigation practices. Financial assistance programs should also be considered in nonpoint source control programs.

IMPLEMENTATION OF BEST MANAGEMENT PRACTICES

Once the best practices for salinity management in the irrigated area are determined, there is a need to develop methods for implementing these practices. Section 10 of this manual discusses many of the issues involved

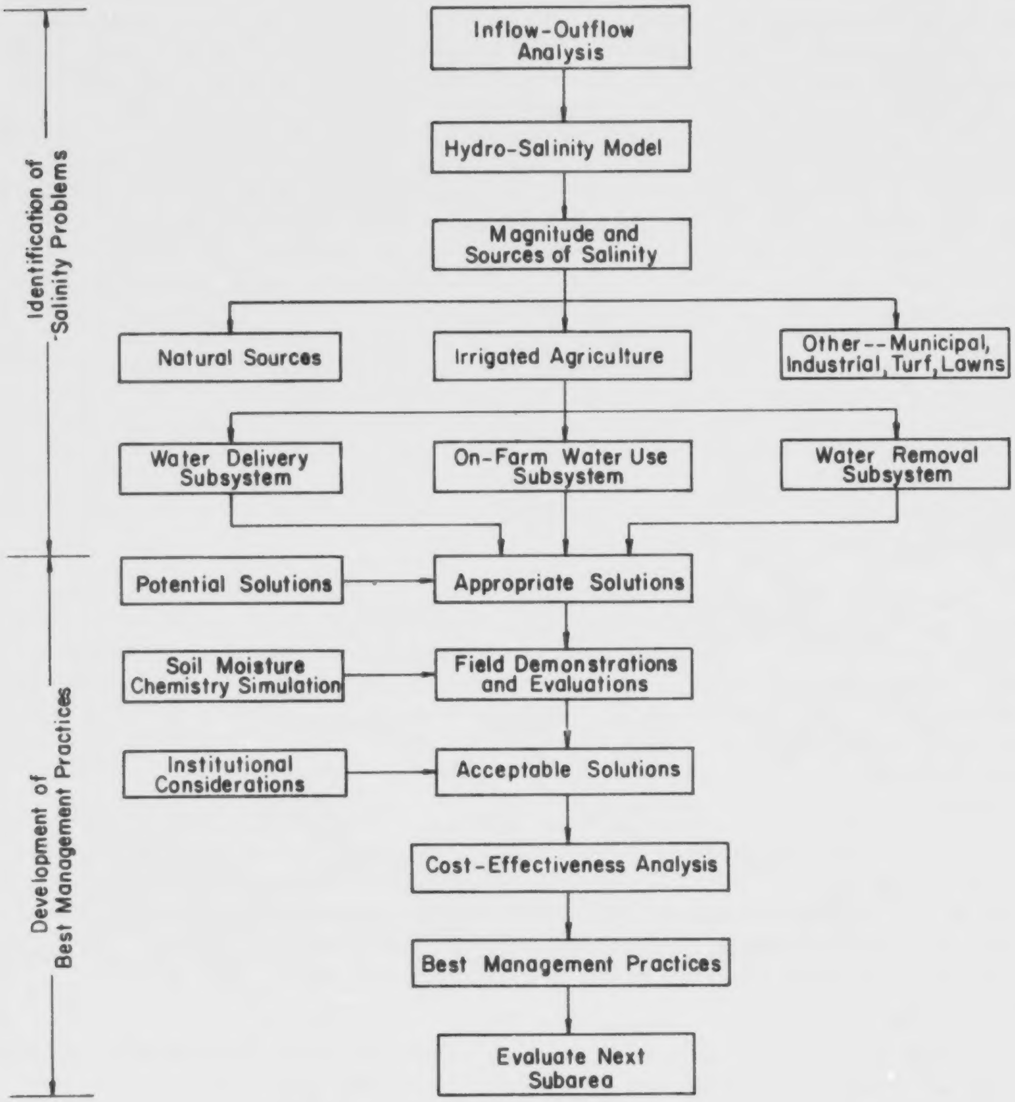
Identification of Salinity Problems
Development of Best Management Practices
Inflow-Outflow Analysis
Hydro-Salinity Model
Magnitude and Sources of Salinity
Natural Sources
Irrigated Agriculture
Other--Municipal, Industrial, Turf, Lawns
Water Delivery Subsystem
On-Farm Water Use Subsystem
Water Removal Subsystem
Potential Solutions
Appropriate Solutions
Soil Moisture Chemistry Simulation
Field Demonstrations and Evaluations
Institutional Considerations
Acceptable Solutions
Cost-Effectiveness Analysis
Best Management Practices
Evaluate Next Subarea

Figure 1. Planning framework for developing best management practices in a subbasin.

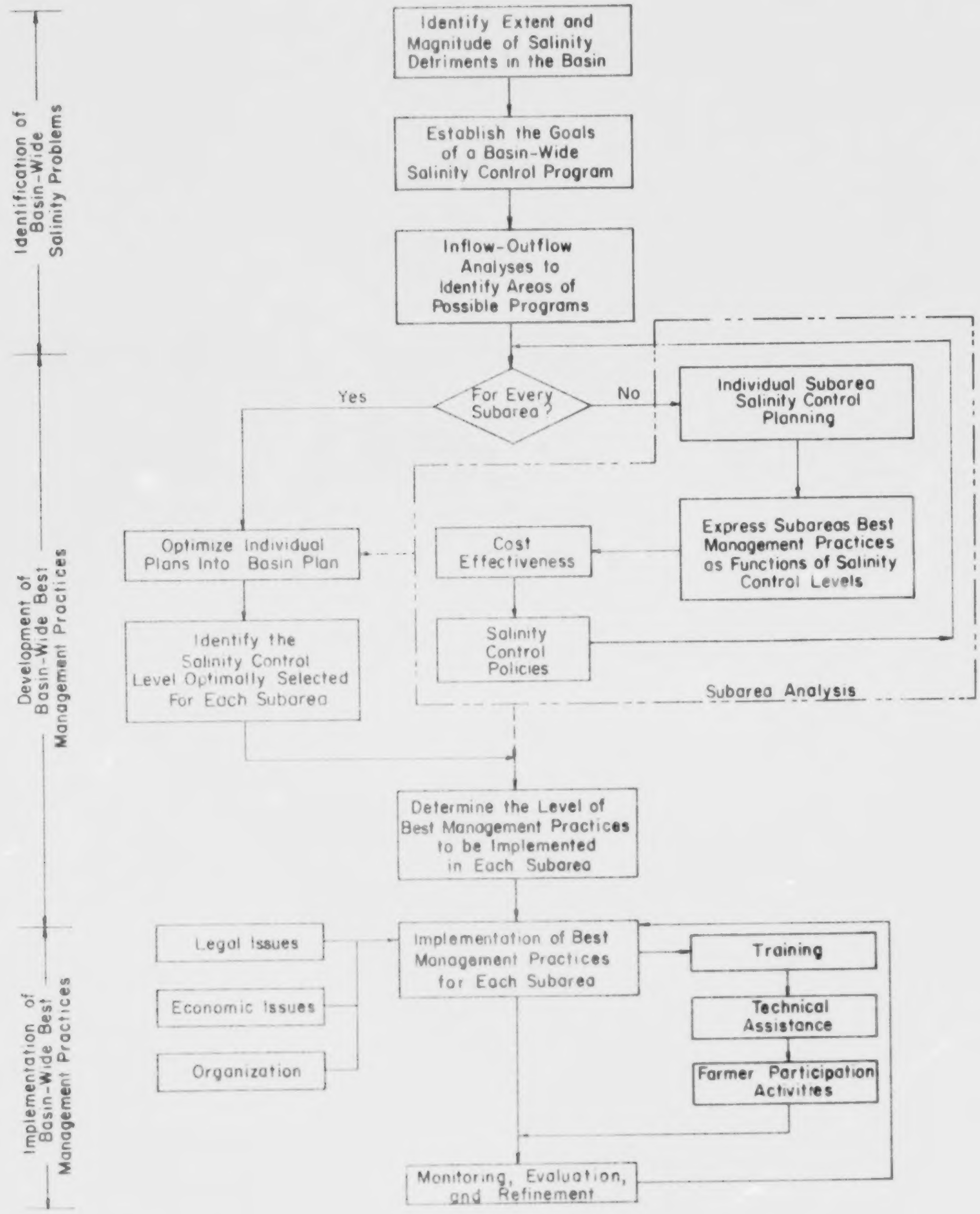
Identification of Basin-Wide Salinity Problems
Development of Basin-Wide Best Management Practices
Implementation of Basin-Wide Best Management Practices
Identify Extent and Magnitude of Salinity Detriments in the Basin
Establish the Goals of a Basin-Wide Salinity Control Program
Inflow-Outflow Analyses to Identify Areas of Possible Programs
For Every Subarea ?
Yes
No
Individual Subarea Salinity Control Planning
Express Subareas Best Management Practices as Functions of Salinity Control Levels
Cost Effectiveness
Salinity Control Policies
Subarea Analysis
Optimize Individual Plans Into Basin Plan
Identify the Salinity Control Level Optimally Selected For Each Subarea
Determine the Level of Best Management Practices to be Implemented in Each Subarea
Legal Issues
Economic Issues
Organization
Implementation of Best Management Practices for Each Subarea
Training
Technical Assistance
Farmer Participation Activities
Monitoring, Evaluation, and Refinement

Figure 2. Planning framework for developing best management practices for salinity management in a river basin.

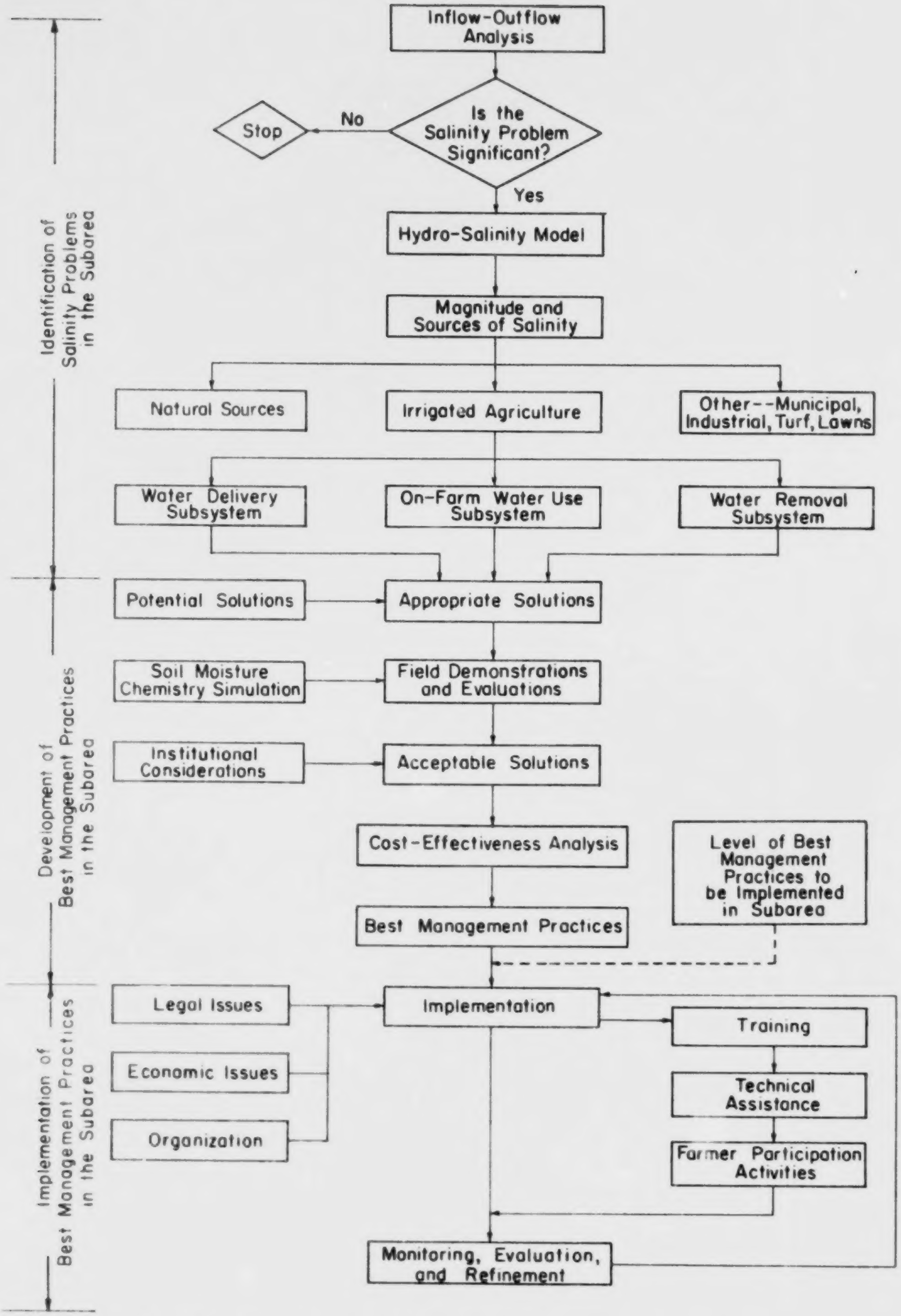
Identification of Salinity Problems in the Subarea
Development of Best Management Practices in the Subarea
Implementation of Best Management Practices in the Subarea
Inflow-Outflow Analysis
Is the Salinity Problem Significant?
No
Stop
Yes
Hydro-Salinity Model
Magnitude and Sources of Salinity
Natural Sources
Irrigated Agriculture
Other--Municipal, Industrial, Turf, Lawns
Water Delivery Subsystem
On-Farm Water Use Subsystem
Water Removal Subsystem
Potential Solutions
Appropriate Solutions
Soil Moisture Chemistry Simulation
Field Demonstrations and Evaluations
Institutional Considerations
Acceptable Solutions
Cost-Effectiveness Analysis
Level of Best Management Practices to be Implemented in Subarea
Best Management Practices
Legal Issues
Economic Issues
Organization
Implementation
Training
Technical Assistance
Farmer Participation Activities
Monitoring, Evaluation, and Refinement

Figure 3. Planning framework for developing best management practices for only one irrigated area.

in implementing solutions to water quality problems in irrigated agriculture and, in particular, salinity. Besides legal and economic issues in implementing technology, there are important questions on how to organize for implementation.

Implementation of salinity management measures requires strong participation by farmers in order to have a successful program. Farmers must be aware of the salinity problems and their solutions. There is an additional obstacle of training technical assistance personnel for this particular work. There is a great necessity for continuing monitoring, evaluation, and refinement of the implementation program.

SECTION 2

IRRIGATION IN THE UNITED STATES

PRESENT WATER AND LAND USE

Agricultural water use has grown steadily throughout the years. The first statistical record of irrigation in the United States was obtained through the Census of Agriculture in 1889. That census recorded 3,361,000 acres (1,360,200 hectares) under irrigation. The most recent Census of Agriculture (1974) recorded 41,429,000 acres (16,765,965 hectares) under irrigation or an increase of more than 1,200 percent in 85 years. In 1975 it was estimated that 160 million acre-feet (19.7 million hectare-meters) of water were diverted for irrigation in the United States of which about 56 percent was consumptively used (Murray and Reeves, 1977). This does not mean the average irrigation efficiency is 56 percent. Rather, the average efficiency is much lower, approximately 35 to 45 percent, because the "excess" water, which is diverted, returns to streams as irrigation return flow by surface and/or subsurface means and is then rediverted for reuse on other lands.

The major irrigated areas in the United States are located in the 17 western states that are shown in Figure 4. The increase in irrigation for the 17 western states in Figure 5 reflects the national increase in irrigated acreage. An examination of Table 1 indicates that in 1977 both California and Texas contained over 8 million acres (3.24 million hectares) of irrigated land; Nebraska had more than 7 million; Idaho, 4 million; and Colorado, Kansas, and Montana contained over 3 million acres (2.8, 1.6, and 1.2 million hectares, respectively) of irrigated land. Arizona, Nevada, New Mexico, Oregon, Utah, Washington, and Wyoming contained between 1 and 2 million acres (0.8 and 0.4 million hectares); while Oklahoma, North Dakota, and South Dakota contained less than 1 million acres (0.4 million hectares) of irrigated land. In addition, Florida had almost 3 million acres. Arkansas had 1.5 million acres, and Louisiana about 0.6 million acres of irrigated land (1.2, 0.6, and 0.24 million hectares, respectively). The estimated irrigation water use by state for 1975 is presented in Table 2. Figure 6 illustrates the relative magnitude of fresh water withdrawals and consumption in the United States for 1975. The estimated quantity of water used for irrigation and irrigation return flows (IRF) for the same year are presented by water resource region in Figure 7.

Irrigation results in large increases in the productivity of croplands. Irrigated lands in the United States amount to approximately 10 percent of the total cropland, and yet produces about 25 percent of the total

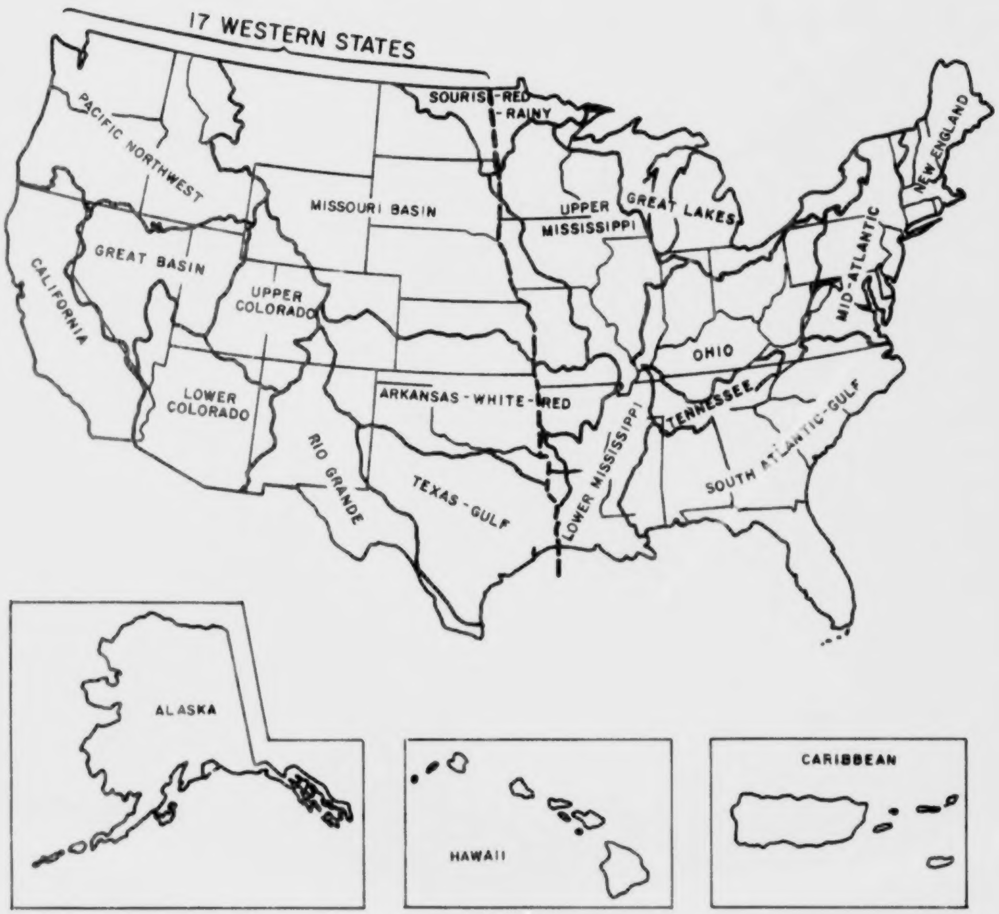
17 WESTERN STATES
PACIFIC NORTHWEST
MISSOURI BASIN
SOURIS-RED-RAINY
UPPER MISSISSIPPI
GREAT LAKES
NEW ENGLAND
MID-ATLANTIC
GREAT BASIN
CALIFORNIA
UPPER COLORADO
OHIO
LOWER COLORADO
ARKANSAS-WHITE-RED
TENNESSEE
SOUTH ATLANTIC-GULF
RIO GRANDE
TEXAS-GULF
LOWER MISSISSIPPI
ALASKA
HAWAII
CARIBBEAN

Figure 4. Map of the United States showing the 17 western states and the commonly used water resource regions (Water Resources Council, 1968).

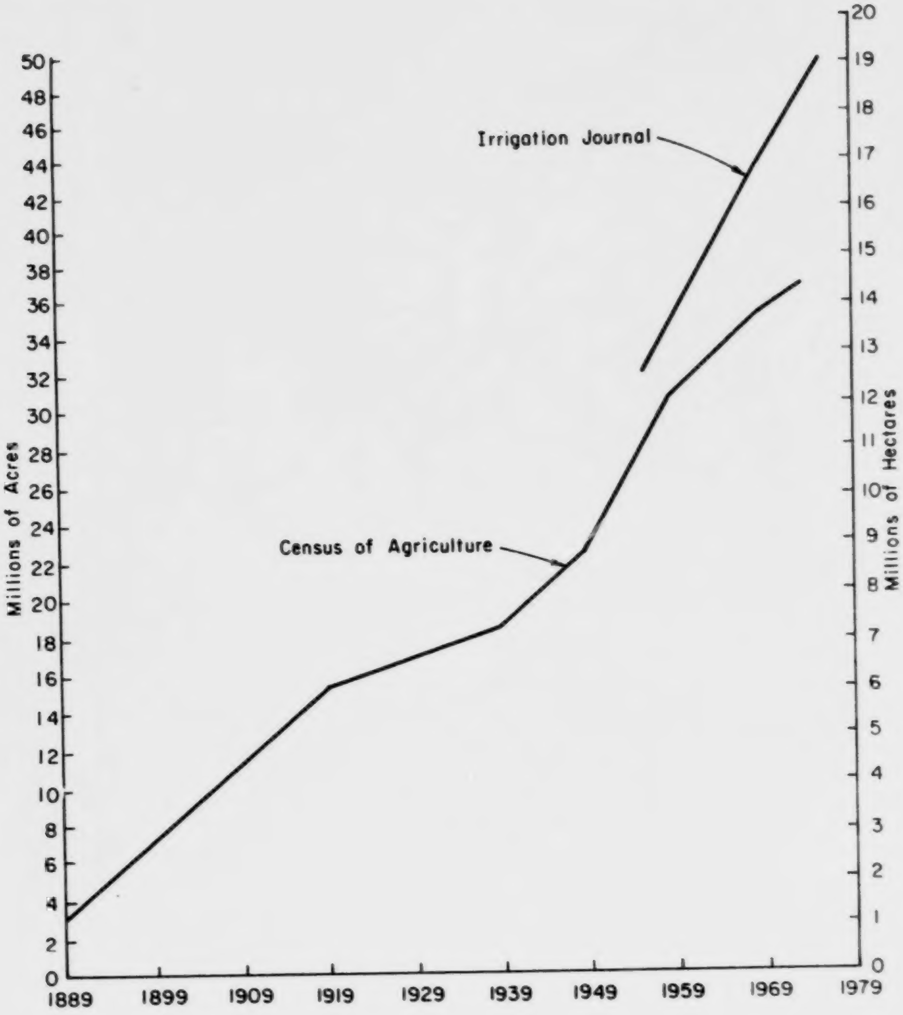

Figure 5. Irrigation development in the 17 western states, 1889-1974 (U.S. Department of Commerce, Bureau of the Census and Irrigation Journal).

TABLE 1. IRRIGATED ACREAGE IN THE UNITED STATES FOR SELECTED YEARS 4/

STATE	IRRIGATED ACREAGE		
	1956 2/	1965 2/	1977 2/
ALABAMA	25,000	25,580	58,600
ALASKA	3/	86	1,890
ARIZONA 1/	1,150,000	1,160,000	1,150,000
ARKANSAS	892,930	1,275,000	1,698,500
CALIFORNIA 1/	7,750,000	8,500,000	8,189,176
COLORADO 1/	2,382,000	3,003,000	3,060,000
CONNECTICUT	20,000	15,000	9,000
DELAWARE	11,000	18,770	34,000
FLORIDA	521,200	1,184,593	2,918,244
GEORGIA	75,000	156,000	592,100
HAWAII	3/	139,810	155,128
IDAHO 1/	2,405,089	3,250,000	3,934,000
ILLINOIS	16,500	26,000	68,000
INDIANA	35,000	17,000	58,250
IOWA	32,000	85,000	165,000
KANSAS 1/	722,575	1,190,000	3,157,500
KENTUCKY	18,225	15,000	27,500
LOUISIANA	711,000	484,475	662,695
MAINE	6,900	6,500	5,555
MARYLAND	12,000	18,800	32,570
MASSACHUSETTS	25,270	27,585	31,300
MICHIGAN	24,360	114,000	135,000
MINNESOTA	28,000	23,000	397,500
MISSISSIPPI	157,000	146,000	402,400
MISSOURI	60,000	75,872	266,558
MONTANA 1/	1,890,000	2,901,078	3,114,150
NEBRASKA 1/	2,012,320	3,491,000	7,165,100
NEVADA 1/	700,000	846,000	1,304,700
NEW HAMPSHIRE	1,100	4,500	6,000
NEW JERSEY	72,150	65,842	174,000
NEW MEXICO 1/	800,000	850,000	1,239,600
NEW YORK	59,024	66,000	53,840
NORTH CAROLINA	38,500	94,797	120,640
NORTH DAKOTA 1/	48,000	80,105	134,310
OHIO	25,000	26,000	43,000
OKLAHOMA 1/	285,175	418,373	951,260
OREGON 1/	1,575,000	1,690,000	1,885,000
PENNSYLVANIA	21,500	25,000	19,000
RHODE ISLAND	1,000	600	3,000
SOUTH CAROLINA	48,994	26,525	36,295
SOUTH DAKOTA 1/	120,000	138,000	371,000
TENNESSEE	29,000	10,000	19,200
TEXAS 1/	6,962,234	7,800,000	8,900,000
UTAH 1/	1,200,000	1,436,295	2,033,769
VERMONT	1,470	2,200	2,200
VIRGINIA	32,000	55,000	61,320
WASHINGTON 1/	947,000	1,236,900	1,630,800
WEST VIRGINIA	1,006	2,300	2,262
WISCONSIN	25,000	72,600	253,000
WYOMING 1/	1,300,000	1,590,000	1,658,960
U.S. TOTAL	35,278,602	43,886,286	58,393,000
17 WESTERN STATES	32,249,393	39,580,851	49,879,325
OTHER STATES	3,029,209	4,305,435	8,513,047

1/ 17 Western States.

2/ From Irrigation Journal Surveys.

3/ Not available.

4/ 1 acre equals 0.4046 hectares.

TABLE 2. WATER DIVERTED AND CONSUMED FOR IRRIGATION BY STATES, 1975. (MURRAY & REEVES, 1977)[1/][2/]

State	Acres irrigated (1,000 acres)[3/]	Total water withdrawn (1,000 acre-feet per year)[4/]				Freshwater consumed (1,000 ac-ft/yr)	Conveyance loss (1,000 ac-ft/yr)	Total water withdrawn (million gallons per day)[5/]				Freshwater consumed (mgd)	Conveyance loss (mgd)
		Ground water	Surface water	Reclaimed sewage	All water			Ground water	Surface water	Reclaimed sewage	All water		
Alabama	32	7.2	17	0	24	24	0	6.6	15	0	22	22	0
Alaska	0	0	0	0	0	0	0	0	0	0	0	0	0
Arizona	1,400	4,700	3,100	60	7,900	6,000	280	4,200	2,800	54	7,000	5,400	250
Arkansas	1,400	2,300	390	0	2,700	2,000	190	2,100	350	0	2,400	1,800	170
California	9,000	18,000	20,000	180	39,000	23,000	5,900	17,000	18,000	160	35,000	21,000	5,300
Colorado	3,100	2,800	7,500	90	10,000	5,700	1,200	2,500	6,700	80	9,300	5,100	1,000
Connecticut	15	.4	4.4	0	4.8	4.8	0	.4	3.9	0	4.3	4.3	0
Delaware	22	14	2.1	0	16	16	0	12	1.8	0	14	14	0
Florida	2,000	1,400	1,800	0	3,200	1,400	240	1,200	1,600	0	2,900	1,300	220
Georgia	120	26	44	0	71	71	0	24	40	0	63	63	0
Hawaii	140	480	580	0	1,100	560	500	430	520	0	950	500	450
Idaho	3,800	3,900	13,000	6.2	17,000	5,300	4,800	3,500	12,000	5.6	15,000	4,700	4,300
Illinois	68	32	14	0	46	46	0	29	12	0	41	41	0
Indiana	43	26	11	0	37	37	0	24	10	0	34	33	0
Iowa	57	21	2.6	0	23	23	0	18	2.2	0	21	21	0
Kansas	3,000	5,200	370	0	5,600	4,300	120	4,600	330	0	5,000	3,800	110
Kentucky	10	.1	2.9	0	3.0	2.9	0	.1	2.[illegible]	0	2.7	2.6	0
Louisiana	780	900	1,300	0	2,200	2,200	690	810	1,100	0	1,900	1,900	610
Maine	21	0	9.5	0	9.5	9.5	0	0	8.5	0	8.5	8.5	0
Maryland	22	4.6	5.9	.2	11	10	0	4.1	5.2	.2	9.5	9.4	0
Massachusetts	39	12	25	0	37	37	0	11	22	0	33	33	0
Michigan	110	27	44	0	72	72	0	24	40	0	64	64	0
Minnesota	140	26	26	0	52	52	0	24	23	0	47	47	0
Mississippi	390	620	140	0	750	380	75	550	120	0	670	340	67
Missouri	260	100	6.0	0	110	85	2.5	91	5.5	0	96	76	2.3
Montana	2,400	120	12,000	0	12,000	3,000	2,800	110	11,000	0	11,000	2,700	2,500
Nebraska	5,600	5,900	2,300	0	8,200	6,400	1,700	5,200	2,100	0	7,300	5,800	1,600
Nevada	860	590	2,900	3.7	3,500	1,700	800	530	2,600	3.3	3,100	1,500	720
New Hampshire	6.0	0	6.1	0	6.1	6.0	0	0	5.4	0	5.4	5.3	0
New Jersey	130	120	40	0	160	120	0	110	36	0	140	110	0

(Continued)

TABLE 2. (Continued)

State	Acres irrigated (1,000 acres) 3/	Total water withdrawn (1,000 acre-feet per year) 4/				Freshwater consumed (1,000 ac-ft/yr)	Conveyance loss (1,000 ac-ft/yr)	Total water withdrawn (million gallons per day) 5/				Freshwater consumed (mgd)	Conveyance loss (mgd)
		Ground water	Surface water	Reclaimed sewage	All water			Ground water	Surface water	Reclaimed sewage	All water		
New Mexico	1,100	1,500	1,800	0	3,200	1,600	24	1,300	1,600	0	2,900	1,400	21
New York	83	21	15	0	36	35	0	19	13	0	32	32	0
North Carolina	500	59	38	0	97	97	0	53	34	0	87	87	0
North Dakota	130	54	130	0	180	170	18	48	120	0	160	150	16
Ohio	41	6.2	14	0	20	18	0	5.5	13	0	18	16	0
Oklahoma	1,000	1,100	180	0	1,300	910	16	1,000	160	0	1,200	820	14
Oregon	2,100	1,000	5,700	4.0	6,700	3,400	1,900	920	5,100	3.6	6,000	3,000	1,700
Pennsylvania	29	6.9	32	0	39	39	0	6.1	28	0	34	34	0
Rhode Island	3.8	.5	4.7	0	5.2	5.2	0	.4	4.2	0	4.6	4.6	0
South Carolina	42	10	22	0	32	32	0	8.9	20	0	29	29	0
South Dakota	200	55	320	0	370	200	160	49	280	0	330	180	150
Tennessee	19	3.6	6.1	0	9.7	9.0	.7	3.3	5.3	0	8.6	8.1	.7
Texas	8,600	10,000	2,600	60	13,000	12,000	480	9,400	2,300	53	12,000	11,000	430
Utah	1,700	540	3,300	1.0	3,900	2,400	430	480	3,000	.9	3,500	2,200	390
Vermont	2.3	.4	2.0	0	2.4	2.4	0	.4	1.8	0	2.2	2.2	0
Virginia	44	4.2	18	0	22	13	3.4	3.7	16	0	20	12	3.0
Washington	1,600	260	5,900	0	6,200	2,500	1,200	230	5,300	0	5,500	2,200	1,000
West Virginia	2.4	0	1.4	0	1.4	1.4	0	0	1.2	0	1.2	1.2	0
Wisconsin	130	57	22	0	79	62	0	51	20	0	71	56	0
Wyoming	1,700	300	7,300	0	7,600	2,200	1,800	270	6,500	0	6,800	2,000	1,600
District of Columbia	0	0	0	0	0	0	0	0	0	0	0	0	0
Puerto Rico-Virgin Islands	66	100	160	0	260	160	60	89	140	0	230	140	54
United States	54,000	63,000	94,000	410	160,000	89,000	25,000	57,000	84,000	360	140,000	80,000	23,000

1/ Including Puerto Rico and Virgin Islands.

2/ Partial figures may not add to totals due to rounding.

3/ One acre equals 0.4046 hectares.

4/ One acre foot equals 0.1233 hectare-meters.

5/ 1 mgd (million gallons per day) equals 0.0183 m^3/sec, also equals 3.07 acre-feet per day.

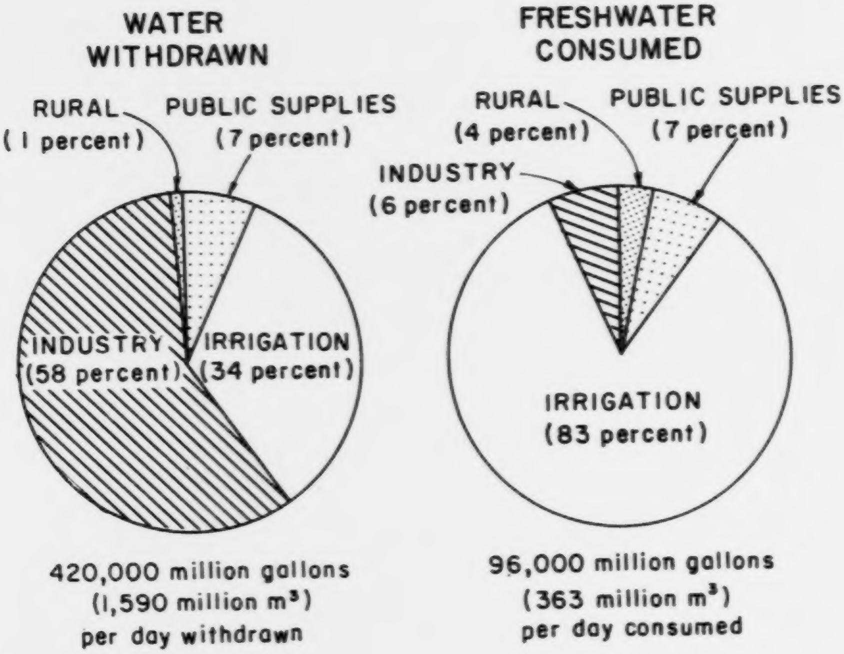

Figure 6. Water withdrawals and consumption in the United States for 1975 (Murray and Reeves, 1977).

agricultural output (FWPCA, 1968). Other factors have also contributed to spectacular gains in productivity. The use of more fertilizer, increased plant populations per acre, improved crop varieties, advanced methods and means of pest control and improved water management have all contributed to high farm productivity. In addition to the increased productivity of irrigated agriculture, several other factors including technological changes have increased the irrigated acreage. These include improved water storage, water conveyance, and irrigation water application methods such as sprinkler irrigation systems and trickle irrigation. Evaporation suppression, weather modification, and phreatophyte control or eradication also have made more water available for agricultural use. Population growth and population shifts have necessitated increased crop productivity due to larger local demands for fresh fruits and vegetables as well as dairy and poultry products.

The Water Resources Council (1968) estimated all water requirements to the year 2020 (Table 3). Their calculations indicate that use of water in irrigated areas will increase by more than 50 percent during the 1965-2020 period. Most of this expanded water use will be in the midwest and southeast portions of the United States.

Large increases in irrigated acreage are due to the development of sprinkler and trickle irrigation systems. These irrigation methods, with

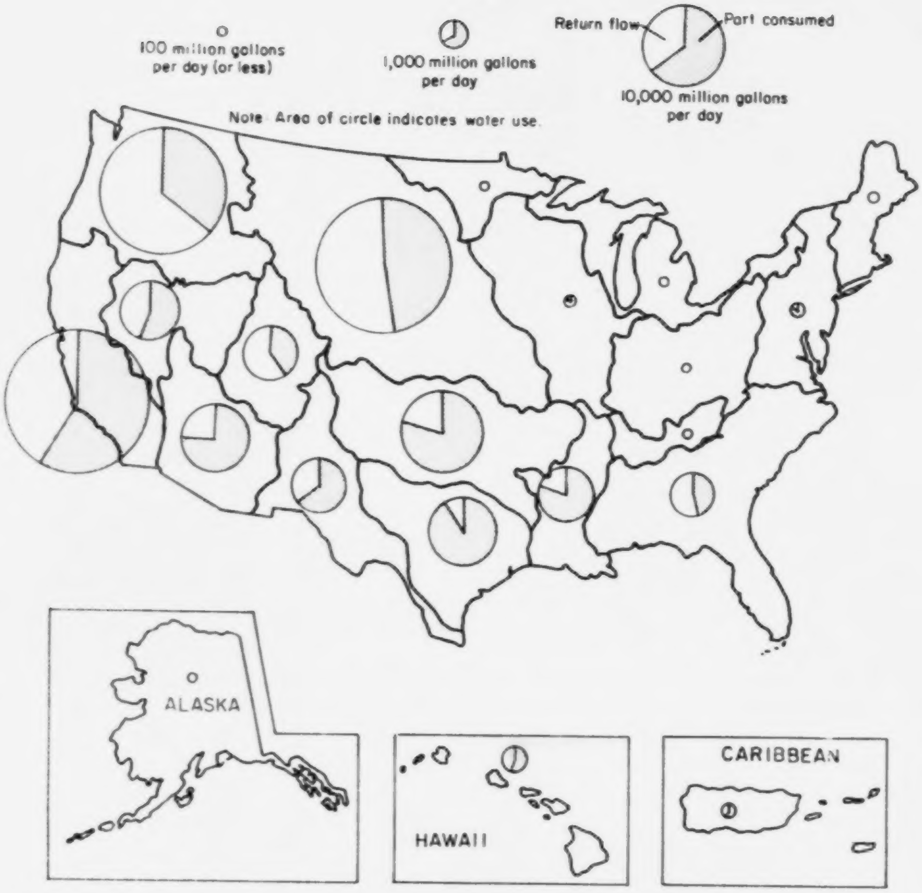
100 million gallons per day (or less)
1,000 million gallons per day
Return flow
Part consumed
10,000 million gallons per day
Note: Area of circle indicates water use.
ALASKA
HAWAII
CARIBBEAN

Figure 7. Estimated consumption of irrigation water and irrigation return flows by water resource regions in the United States for 1975 (Murray and Reeves, 1977).

Note: 1 million gallons per day equals 0.0183 m^3/sec and equals 3.07 acre-feet per day.

TABLE 3. ESTIMATED WATER USE AND PROJECTED REQUIREMENTS, (U.S. WATER RESOURCES COUNCIL, 1968) MILLION GALLONS DAILY)[1]

TYPE OF USE	Used 1965	Projected Requirements 1980	Projected Requirements 2000	Projected Requirements 2020	Used 1965	Projected Requirements 1980	Projected Requirements 2000	Projected Requirements 2020
	Withdrawals				Consumptive Use			
Rural domestic	2,351	2,474	2,852	3,334	1,636	1,792	2,102	2,481
Municipal (public-supplied)	23,745	33,596	50,724	74,256	5,244	10,581	16,478	24,643
Industrial (self-supplied)	46,405	75,026	127,365	210,767	3,764	6,126	10,011	15,619
Steam-electric power: . .								
Fresh	62,738	133,963	259,208	410,553	659	1,685	4,552	8,002
Saline	21,800	59,340	211,240	503,540	157	498	2,022	5,183
Agriculture:								
Irrigation	110,852	135,852	149,824	160,978	64,696	81,559	89,964	96,919
Livestock	1,726	2,375	3,397	4,660	1,626	2,177	3,077	4,238
Total	269,617	442,626	804,610	1,368,088	77,782	104,418	128,206	157,085

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[1] 1 million gallons per day = 0.0183 m^3/sec.

increased flexibility and efficient water control, have enabled irrigation of more kinds of soils than surface water application methods allow. Therefore, more land can be classified as irrigable. As a direct result, many thousands of hectares, which were previously considered suitable only for dryland farming or as wasteland, are being irrigated today and producing high crop yields. This phenomenon is particularly evident in eastern Colorado, Nebraska, and Kansas. Also, the higher application efficiencies in established irrigated areas, due to these methods plus seepage control by lining conveyance systems, have permitted an expansion of the irrigated area with the "saved" water, sometimes at the expense of other irrigated areas depending on return flows.

Development of new water sources such as groundwater in California, Arizona, New Mexico, Texas, Oklahoma, Kansas, Nebraska, and Idaho has been very important for the irrigation development of these areas. Figure 8 indicates the United States trends in use of irrigation water supplies, where the increased use of groundwater is clearly evident. This rapid development of groundwater has presented numerous problems with existing surface water rights, land subsidence, and groundwater pollution. Many areas that utilize groundwater supplies for irrigation are severely affected by increased costs for energy. Also, in an effort to reduce energy costs, many growers in Nebraska and Kansas use only off-peak electric power for pumping. Off-peak power is power which is available at times other than at peak demand intervals and has a lower cost per kilowatt-hour.

Areas in the United States, specifically the Midwest and Southeast, that annually receive sufficient precipitation to satisfy crop requirements have installed supplemental irrigation systems. This is necessary since rainfall does not often fall at exactly the right time in the right quantities. Timely irrigations at a critical crop growth stage, applying only 0.5 to 1 foot (150 to 300 mm) of water per year, can more than double yields. Sprinklers form a large number of these supplemental irrigation systems due to their adaptability to large topographic differences and soil conditions.

In 1950, there were about 26 million acres of irrigated land in the United States of which more than 92 percent was in the 17 western states. In 1974, this dropped to 89 percent (U.S. Department of Commerce, 1976) and in 1977 it dropped to 85 percent (Irrigation Journal, 1978). The percentage of irrigated agricultural land in other areas of the United States is expected to increase even more in the future.

TRENDS IN AGRICULTURAL WATER USE

The amount and distribution of water in the future will depend on several factors; primarily climate, cropping patterns, irrigated acreage and level of efficiency attained by the irrigators. The projected water consumption for all uses is presented by regions in Table 4. Regional projections of irrigated land, irrigation withdrawal and irrigation consumption are presented in Tables 5, 6, and 7.

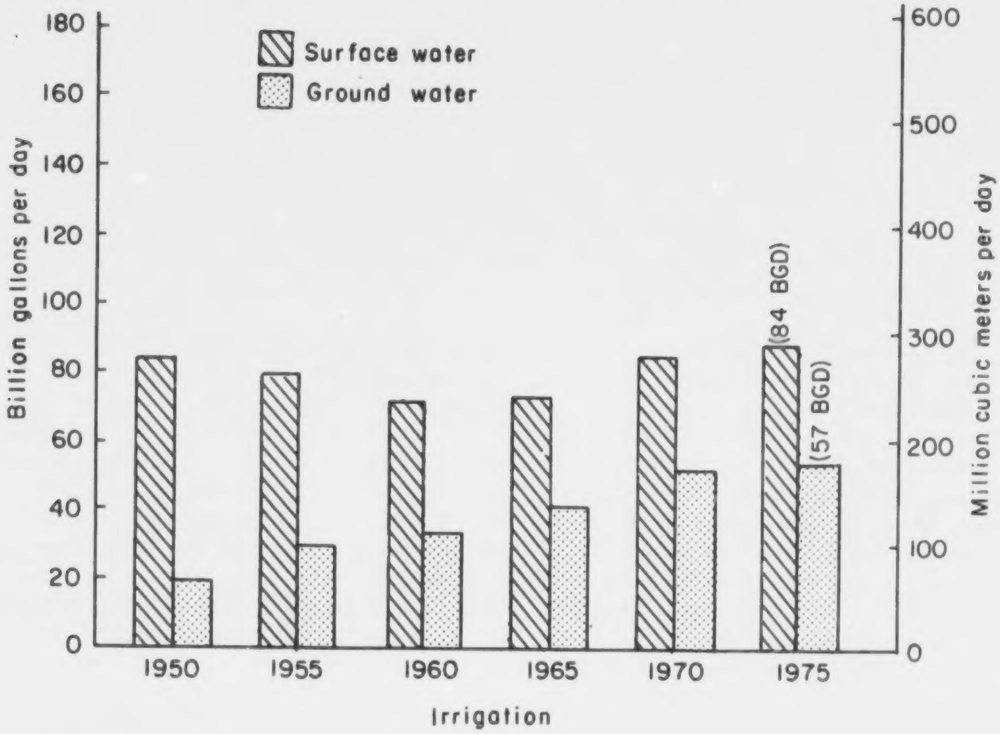

Figure 8. Trends in use of irrigation water supplies (Murray and Reeves, 1977).

In examining data concerning irrigated agriculture in the United States, we note there are several trends expected to continue, providing there are no restraints by the government. Some of these trends, as seen by the authors, are discussed in the following paragraphs.

It is expected that irrigation will primarily expand in the Central and Southeast portions of the United States where adequate water supplies are available, rather than in the West. This development will be private and localized rather than governmental project developments.

There are many indications that there will be increased demands for water from energy and other industrial and municipal users, especially in the West. In addition, strong demands made by recreational and power generation interests will continue. A strong trend toward higher water prices, with the users paying all the costs of water, will occur. In arid areas, irrigation of cereal, forage, and fiber crops will become economically less feasible, and much of the production of these crops will shift to the Midwest and South where natural conditions are more favorable. The arid West will continue to cultivate specialty crops in order to remain competitive because of the higher values of these crops and high productivity potential

TABLE 4. REGIONAL ESTIMATIONS OF WATER USE AND PROJECTED REQUIREMENTS (U.S. WATER RESOURCES COUNCIL, 1968) (MILLION GALLONS DAILY)[1]

REGION	Used	Projected Requirements			Used	Projected Requirements		
	1965	1980	2000	2020	1965	1980	2000	2020
	Withdrawals				Consumptive Use			
North Atlantic	37,467	54,920	113,860	236,290	2,023	2,870	4,960	8,490
South Atlantic-Gulf . . .	20,560	53,180	87,440	130,190	2,695	3,395	5,655	8,265
Great Lakes	25,119	47,893	96,594	190,960	1,199	1,881	3,183	5,484
Ohio	28,255	41,749	65,109	90,163	1,134	1,619	2,539	3,623
Tennessee	5,767	12,252	13,877	18,106	331	572	834	1,132
Upper Mississippi	8,179	14,800	30,587	41,266	770	1,103	1,778	2,624
Lower Mississippi	5,571	12,816	27,967	39,442	1,470	3,012	4,453	6,251
Souris-Red-Rainy	391	936	2,002	2,758	77	215	494	544
Missouri	19,344	23,264	27,876	31,572	10,554	13,160	14,979	16,378
Arkansas-White-Red	9,410	17,279	25,336	31,589	5,874	8,482	10,587	12,329
Texas-Gulf	16,410	29,080	57,330	92,640	7,289	9,435	10,890	12,300
Rio Grande	7,289	8,330	9,510	11,680	4,403	4,676	4,991	5,466
Upper Colorado	4,017	5,675	6,575	6,725	1,982	2,700	3,100	3,140
Lower Colorado	6,913	8,497	8,428	8,889	3,448	4,075	4,645	5,310
Great Basin	5,115	7,055	7,550	7,800	2,253	3,299	3,562	3,776
Columbia-North Pacific . .	29,631	41,407	90,135	156,735	10,521	13,581	17,325	21,616
California	37,300	56,290	120,510	244,760	20,944	29,205	32,660	38,190
Alaska	162	535	901	4,206	12	50	96	184
Hawaii	1,597	2,658	4,698	8,587	533	728	1,000	1,368
Puerto Rico	1,120	4,010	8,325	13,730	270	360	475	615
Total	269,617	442,626	804,610	1,368,088	77,782	104,418	128,206	157,085

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[1] 1 million gallons per day = 0.0183 m^3/sec = 3.07 acre-feet per day.

TABLE 5. REGIONAL PROJECTIONS OF IRRIGATED LAND IN THE CONTERMINOUS UNITED STATES (U.S. WATER RESOURCES COUNCIL, 1968) (THOUSANDS OF ACRES)[1/]

REGION	1960	1965	1980	2000	2020
North Atlantic	240	310	380	550	700
South Atlantic-Gulf	850	1,500	1,800	2,750	3,750
Great Lakes	100	140	230	350	470
Ohio	35	55	90	180	260
Tennessee	15	20	30	40	50
Upper Mississippi	80	140	210	390	550
Lower Mississippi	700	900	2,100	3,050	4,150
Souris-Red-Rainy	10	15	90	240	250
Missouri	6,600	7,400	8,050	9,000	9,600
Arkansas-White-Red	3,100	3,800	5,600	6,400	6,850
Texas-Gulf	5,100	5,500	5,500	5,500	5,500
Rio Grande	1,950	2,000	2,050	2,050	2,050
Upper Colorado	1,370	1,440	1,800	2,000	2,000
Lower Colorado	1,520	1,660	1,750	1,800	1,800
Great Basin	1,700	1,860	1,950	2,000	2,000
Columbia-North Pacific	5,450	6,250	7,700	9,500	11,200
California	8,420	8,850	10,150	10,750	11,100
Total	37,240	41,840	49,480	56,550	62,280

[1/] 1 acre = 0.4046 hectares.

TABLE 6. REGIONAL PROJECTIONS OF IRRIGATION WITHDRAWALS (U.S. WATER RESOURCES COUNCIL, 1968) (MILLION GALLONS DAILY)[1]

REGION	1965	1980	2000	2020
North Atlantic	151	230	330	420
South Atlantic-Gulf	3,270	3,900	6,000	8,200
Great Lakes	75	110	170	230
Ohio	24	40	80	115
Tennessee	8	18	23	29
Upper Mississippi	95	110	200	280
Lower Mississippi	1,320	3,030	4,400	6,000
Souris-Red-Rainy	24	200	562	576
Missouri	16,039	19,300	21,600	23,000
Arkansas-White-Red	6,960	9,400	10,700	11,500
Texas-Gulf	7,450	9,400	9,000	8,500
Rio Grande	6,671	6,840	6,840	6,840
Upper Colorado	3,880	5,300	5,350	4,900
Lower Colorado	6,400	7,700	7,000	6,500
Great Basin	4,575	6,200	6,100	5,800
Columbia-North Pacific	26,400	31,400	37,500	42,500
California	26,200	30,950	31,700	32,600
Subtotal	109,542	134,128	147,555	157,990
Alaska	[2]	4	9	18
Hawaii	1,060	1,420	1,910	2,570
Puerto Rico	250	300	350	400
Total	110,852	135,852	149,824	160,978

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[1] 1 million gallons per day = 0.0183 m^3/sec = 3.07 acre-feet per acre.

[2] Insignificant.

TABLE 7. REGIONAL PROJECTIONS OF IRRIGATION CONSUMPTION (U.S. WATER RESOURCES COUNCIL, 1968) (MILLION GALLONS DAILY)[1]

REGION	1965	1980	2000	2020
North Atlantic	150	230	330	420
South Atlantic-Gulf	1,400	1,600	2,450	3,350
Great Lakes	68	95	140	190
Ohio	24	40	80	115
Tennessee	8	16	21	26
Upper Mississippi	83	95	170	240
Lower Mississippi	890	2,180	3,170	4,320
Souris-Red-Rainy	24	150	402	416
Missouri	9,798	12,100	13,500	14,400
Arkansas-White-Red	5,030	6,800	7,800	8,300
Texas-Gulf	5,810	7,100	7,100	7,100
Rio Grande	4,165	4,270	4,270	4,270
Upper Colorado	1,934	2,600	2,880	2,880
Lower Colorado	3,170	3,630	3,760	3,760
Great Basin	2,100	3,040	3,110	3,110
Columbia-North Pacific	10,050	12,900	15,900	18,700
California	19,290	23,800	23,700	23,800
Subtotal	63,994	80,646	88,783	95,397
Alaska	[2]	3	6	12
Hawaii	477	640	860	1,150
Puerto Rico	225	270	315	360
Total	64,696	81,559	89,964	96,919

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[1] 1 million gallons per day = 0.0183 m^3/sec.

[2] Insignificant.

in that climate. It is expected that the increasing trend towards fewer but larger farms will persist.

Future expansion of irrigation in the West will face critical scrutiny because of environmental concerns and cheaper production of many food materials elsewhere. New water demands will create policy emphasis towards water resource development via water markets (or water banking), and mandatory increases in irrigation efficiency, improved water management practices and other water conservation measures. This would not necessarily result in decreased acreage of irrigated cropland, but would require much higher application efficiencies with an expected shift towards better irrigation methods. The total amount of water use for irrigation would not decline, but the areal use patterns will shift. More emphasis will be placed on new food production technologies and plant genetic research. Future increases in crop production will be contingent upon more effective management practices in the utilization of fertilizers and pesticides with concern for their effects on the environment.

There will be more emphasis towards reuse and desalination or other treatment of existing water supplies. There will be expanded use of irrigated agriculture as tertiary treatment from municipal sewage or industrial effluent, and for disposal of thermal pollution (waste heat) from steam power generator facilities. In these instances, there will be an even greater concern for controlling the irrigation return flow from these areas, and managing the quality and quantity of these flows.

SECTION 3

IRRIGATED AGRICULTURE AND SALINITY PROBLEMS

Irrigation is one of the most important agricultural practices developed by man. Irrigation, practiced in some form since the earliest recorded history of agriculture, was the economic base for many ancient civilizations. Today, as then, irrigated farming not only increased productivity, but provides flexibility by allowing shifting from the relatively few dryland crops to other higher value crops such as corn, cotton, and sugar beets that are in greater demand. Irrigation strengthens other facets of a region's economy since it usually creates more employment opportunities than rain-fed agriculture through its intensive and diversified cultivation, stimulation of agri-businesses, the provision of products for export, and creation of a healthy domestic market (Skogerboe and Law, 1971).

Irrigation, however, is not without problems. To maintain productivity in irrigated agriculture, salts applied onto the croplands through irrigation water must be moved below the root zone in order not to impair plant growth. Therefore, it is mandatory that water diverted to a crop exceed the actual water requirement of the plants to include sufficient water for evapotranspiration, leaching, seepage losses, and other transit or ditch losses, which in many cases, are substantial.

The quantity of irrigation water diverted from a river usually far exceeds the cropland water requirement. Data from many irrigation regions indicate that seepage losses from canals and laterals throughout the irrigation water delivery systems are high. Excess water in the delivery system is usually bypassed back to the stream and surface flows. Added to this problem is the overapplication of water on farm fields, which results in excessive surface runoff from the lower end of the field (tailwater runoff), and/or excessive quantities of water moving below the root zone (deep percolation). This surface and subsurface water which returns to the stream is referred to as irrigation return flow.

In some areas, the combination of seepage and deep percolation losses can cause groundwater levels to rise near the surface (waterlogging), which is undesirable. In many irrigated regions, groundwater levels are sufficiently close to the root zone that water and salts are supplied to that region by upward movement of groundwater due to capillarity. When upward moving water reaches the soil surface and evaporates, salts are left behind on the ground surface. This process of salinization not only results in declining agricultural production, but has caused land to become barren.

In some areas, such as the South Platte River Basin in Colorado, deep percolation and seepage losses are politically and socially desirable since many of the water rights (surface and groundwater) are dependent on the irrigation return flow. In this area, the groundwater is not seriously polluted with salts, except possibly nitrates, and salinity increases are primarily due to concentrating effects.

Historically, some degree of salt concentration due to irrigation was tolerated as the price for development (Law and Skogerboe, 1972). In some areas, however, there has been so much laxity that water and land quality degradation has become a serious matter. As pressures on water resources become greater due to the necessity to increase the quantity and quality of food production, there is a mounting concern for control of water quality deterioration and soil salinization. The need for more precise information as a basis for wise policy action is of critical importance (Skogerboe and Law, 1971).

The major problems resulting from irrigation are due to the basic fact that plants are large consumers of water resources. Growing plants extract water and leave salts behind. This results in a concentration of the dissolved mineral salts that are present in all natural water which is applied to the land. Irrigation also adds to the salt load by leaching natural salts arising from weathered minerals occurring in the soil profile, or deposited in the geologic substrata. Irrigation return flows, surface and subsurface, provide the vehicle for conveying the concentrated salts and other pollutants to a receiving stream or groundwater reservoir.

Whenever water is diverted from a river for irrigation use, the quality of the return flow becomes degraded. The degraded return flow then mixes with the natural flows in the river system. This mixture is then diverted by downstream users to satisfy their water demands. This process of diversion and return flow may be repeated many times along the course of a river. In the case of the original diversion, if the increase in pollutants contained in the return flow is small in comparison to the total river flow, water quality might not be degraded to an extent that it would be unfit for use. However, if the quantity of pollutants, such as salinity, in the return flow is large in relation to the river flow, it is likely the water will not be suitable for the next user unless objectionable mineral constituents are removed. In fact, the total salt burden of many of our western streams may be as much as 40 percent man-caused (Law and Bernard, 1970). It must be remembered that in many areas the mass emissions of salt are not linearly proportional to the volume of irrigation return flows, and this relationship must be determined before formulating the best management practices for that area.

The amount of pollution which can result from irrigated agriculture is dependent upon the water management practices, agricultural (cultural) practices and soil chemical and physical properties. Water management practices include the operation and maintenance of the water conveyance systems and the water application method including the amount, timing and frequency of the irrigations. Agricultural practices include seedbed preparations, planting, and other tillage operations, as well as fertilizer and chemical applications.

Since the same water is usually diverted many times from the major rivers, there is a continual water quality degradation in the downstream direction. Consequently, as water resources become increasingly utilized without controls, the quality in the lower reaches of the river will likely be degraded to such a point that remaining flows will be unsuitable for many uses. It is even possible that the waters arriving at the lower portion of the river basin have become so polluted that some existing uses must be discontinued. The Utah State University Foundation (1969) presents an excellent discussion of the characteristics and problems of pollution associated with irrigation return flows.

Major Water Problems

Water Quantity--

In most arid and semi-arid areas of the world, there is the problem of proper timing of water availability. For example, in the western United States, most of the water which is available for irrigation results from runoff from the high mountain snowpacks. This surface runoff is usually exhausted by late June, and without storage facilities such as reservoirs, there would be very little water for the maximum irrigation demands which occur in July and August. Due to the time lag or storage effects, subsurface irrigation return flows in these areas will often increase the natural flows in the streams, resulting in a larger quantity of water available later in the season.

Maintaining or increasing agricultural productivity in an irrigated area requires that a favorable salt balance be achieved in the root zone. Furthermore, the salt in the applied water must be leached to deeper soil horizons, groundwater or the drainage system to the extent that the mass of salts leaving the area must equal or exceed that received in the water supply. It is important that the appropriate amount of water is applied, otherwise, groundwater levels will rise until the water table is near the ground surface. In this case an expensive relief drainage facility would have to be constructed. Thus, a balance must be reached such that a sufficient amount of water is applied to the croplands to supply moisture for crop growth and leaching of salts from the root zone, but not so much that groundwater levels approach the surface. Historically, many societies applied too much water to their lands, and this continues in many areas of the world today.

In order that water does not limit crop yields, a suitable amount of water must be applied to the cropland at the right times. The timing and quantity of required irrigation water is primarily a function of climate, soils, and the growth stage of the crop.

In many regions, increasing urbanization and industrialization requires the reallocation of agricultural water in order to meet new water demands. To accommodate these water reallocations, improved water management practices must be instituted by the agricultural sector, thereby reducing agricultural water diversion requirements.

Improved irrigation practices will actually save or conserve little water, except for reductions in consumptive use by phreatophytes and evaporation from high water tables areas. Improved practices do improve water quality and affect the time distribution of the natural stream flows. However, improved irrigation practices will generally not result in more water being available in the river for fishery enhancement and recreational uses. For example, when considering the consumption of water in an irrigated area, the only actual water losses, that is, water permanently removed from the area, are due to evapotranspiration from crops and phreatophytes, which is fairly constant on a yearly average, or water that percolates to "deep" aquifers which are too deep to have returns to the stream. The remainder of the water is either surface or subsurface return flows. If the total diversions to the cropland were reduced, this "excess" water might be available for redistribution to other upstream users if this water, which was previously return flows, was not part of a downstream water right.

In some cases, improved irrigation practices and reduced return flows may actually damage a downstream water right. This would result because of a change in the temporal distribution of stream flows. For example, the South Platte River in Colorado was an intermittent stream before the introduction of irrigated agriculture in the drainage area. Presently, the stream flows continuously throughout the year as a result of the irrigation return flows. In this case, the existing recreational facilities and downstream water rights might be adversely affected by the rigid implementation of best management practices in the area. In this example, there are also interstate agreements which must be met. The above example illustrates the site-specific nature of irrigation return flow problems.

Water Quality--

The quality of water coming from most upland watersheds in the West is excellent. At the base of hills or mountain ranges, large quantities of water are diverted to valley croplands. Much of the applied water, perhaps 50 to 70 percent, is lost to the atmosphere by evapotranspiration. The remaining water supply is irrigation return flow. This return flow will be either surface runoff (spillage and field tailwater), shallow horizontal subsurface interflows, or will move vertically through the soil profile (seepage and deep percolation) until it reaches a perched water table or the groundwater reservoir. There it can be pumped and used again or be transported through the groundwater reservoir until it reaches a river channel from which it is rediverted further downstream.

Water transpired by plants and water lost by evaporation from soil and open water surfaces is salt free. Water that percolates through the soil profile contains the majority of the salts left by the consumed water and contains a higher concentration of salts than the applied water. This is referred to as the "concentrating" effect. This concentrating effect can also result from interbasin diversions of high quality water, which reduces the water in the river for dilution. As water moves through the soil profile, it may dissolve additional naturally occurring salts resulting from the weathering of the soil minerals. Some salts will react with other chemicals in the soil and be precipitated, while an exchange between some salt ions in the water and soil occurs simultaneously. Additional salts may be picked up by deep percolation passing through salt bearing strata in its way to the stream-drainage system (Law and Bernard, 1970). Salts picked up by the water, which are in addition to the salts applied to the land, are termed salt "pickup." The total salt load is the net sum of the original salt in the applied water resulting from the concentrating effect plus the salt pickup.

Whether irrigation return flows come from surface runoff or return to the system via the soil profile, water can be expected to undergo a variety of quality changes due to varying exposure conditions. Surface return flows consist mainly of precipitation and tailwater runoff from irrigated land. Because of its limited contact and exposure to the soil particles, the following changes in quality might be expected between application and runoff: (a) an increase in sediments and other colloidal material, which results in the slightly increased concentration of dissolved solids, the addition of variable amounts of pesticides, and the addition of variable amounts of fertilizer elements; (b) an increase in crop residues and other debris floating from the soil surface; and (c) increased bacterial content (Utah State University Foundation, 1969).

Subsurface flows that move through the soil profile will be affected differently than the surface runoff. Because of its more intimate contact with the soil and the dynamic soil-plant-water regime, the following changes in quality are predictable: (a) a considerable increase in dissolved solids concentration; (b) a change in relative distribution of various cations and anions; (c) a variation in the total salt load depending on whether there was deposition or leaching; (d) little or no sediment or colloidal material; (e) increase in nitrate content; (f) little or no phosphorus content; (g) a general reduction of oxidizable organic substances; and (h) a reduction of pathogenic organisms and coliform bacteria. Each type of return flow will affect the receiving water in proportion to respective discharges and the relative quality of the receiving water (Utah State University Foundation, 1969).

The quality of irrigation water and return flow is determined largely by the amount and nature of the dissolved and suspended materials it contains. In natural waters, the materials consist of dissolved inorganic salts leached from rocks and soil minerals after contact by water. Irrigation, municipal and industrial use and reuse of water concentrates these salts and adds additional kinds and amounts of pollutants. Many insecticides, fungicides, bactericides, herbicides, nematocides, as well as plant hormones, detergents, salts of heavy metals, and many organic compounds, leave water less usable for irrigation and other uses. From this information it can be concluded that increased salinity concentrations and salt loading result primarily from subsurface irrigation return flows. A schematic representation of these processes is presented in Figure 9.

SOIL-WATER-PLANT RELATIONSHIPS

Soil, water, and plant relationships of particular importance to irrigated agriculture include: (a) evapotranspiration; (b) capacity of the soil to hold water and still be well drained; (c) flow characteristics of water in the soils; (d) physical properties of the soil matrix including

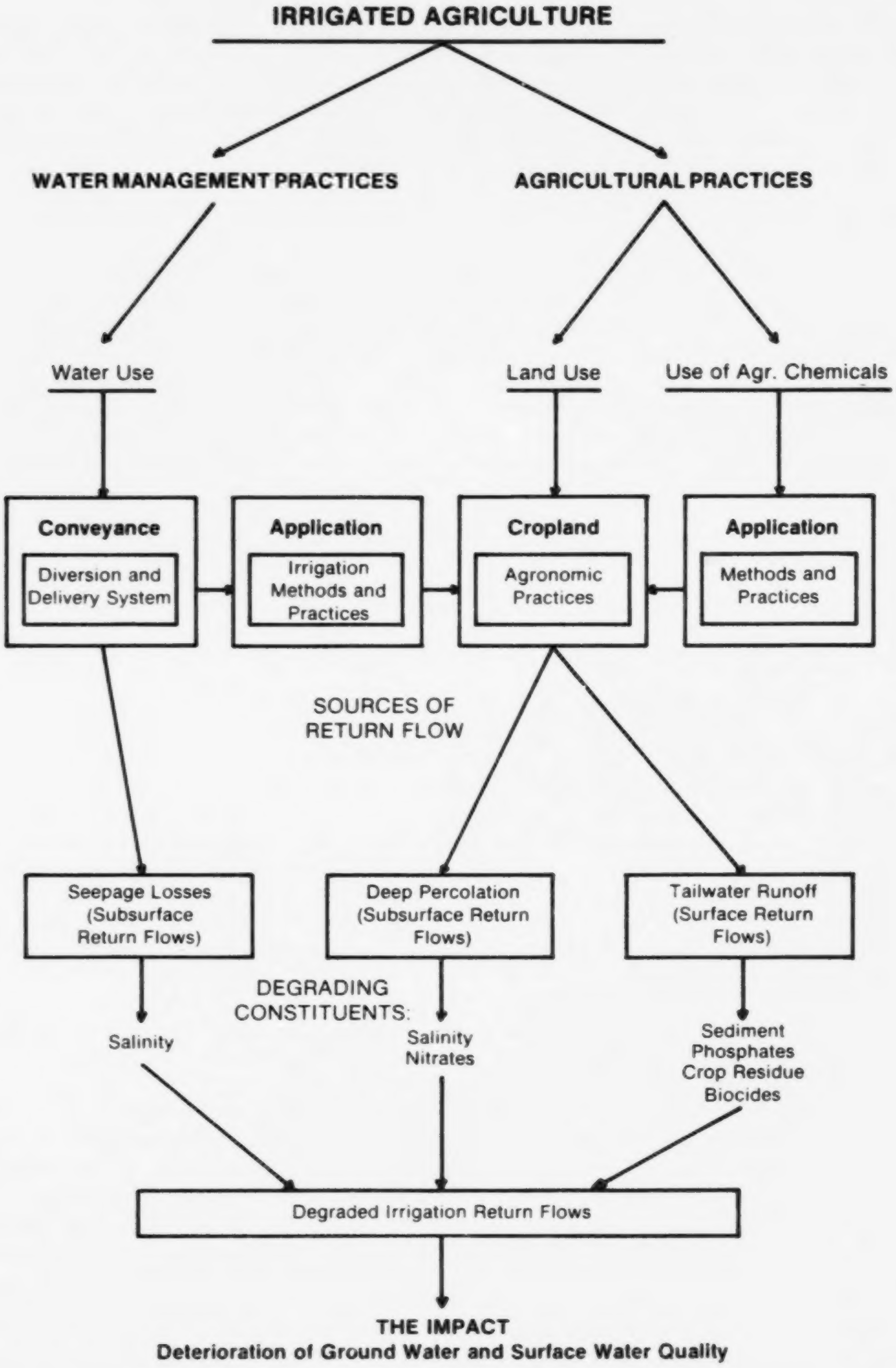

IRRIGATED AGRICULTURE
WATER MANAGEMENT PRACTICES
AGRICULTURAL PRACTICES
Water Use
Land Use
Use of Agr. Chemicals
Conveyance
Diversion and Delivery System
Application
Irrigation Methods and Practices
Cropland
Agronomic Practices
Application
Methods and Practices
SOURCES OF RETURN FLOW
Seepage Losses (Subsurface Return Flows)
Deep Percolation (Subsurface Return Flows)
Tailwater Runoff (Surface Return Flows)
DEGRADING CONSTITUENTS:
Salinity
Salinity
Nitrates
Sediment
Phosphates
Crop Residue
Biocides
Degraded Irrigation Return Flows
THE IMPACT
Deterioration of Ground Water and Surface Water Quality

Figure 9. Schematic representative of the potential for nonpoint source pollution from irrigated agriculture (Radosevich & Skogerboe, 1977).

organic matter content, soil depth, soil texture, and soil structure; and (e) soil chemical relationships including translocation and precipitation of soluble salts and nutrients due to movement, use, and evaporation of the soil water. Knowledge of all these relationships and their influence on each other is critical to those desiring to improve irrigation practices and obtain the best, most efficient use of water.

Evapotranspiration

The total evaporation occurring from soil and plant surfaces and the plant transpiration (evaporation from the parenchyma cells through the stomatal cells) is called evapotranspiration (ET). In addition to ET, plants will use a small amount of water in tissue building. The sum of the ET and the water use in tissue building is called consumptive use. However, because the water removed by plant tissues is usually very small compared to ET, the terms consumptive use and evapotranspiration are commonly used interchangeably. Evapotranspiration (ET) can be measured by several methods which are discussed in Section 8. These measured values are used to calibrate the numerical calculation of ET for both crops and phreatophytes to local conditions. Phreatophytes are water-loving vegetation such as cottonwood trees, willows, salt cedars and cattails, which from an agricultural viewpoint, nonbeneficially consume large amounts of water.

Soil Moisture

If there is either excessive water (waterlogging), or insufficient water, crop growth will be retarded. While irrigation is an artificial means of adding water to the soil to prevent moisture deficiencies, poor irrigation practices can create a waterlogging problem. As commonly defined, the available moisture is the water which is held in soils at a negative apparent pressure range from one-third bar (field capacity) to 15 bars (permanent wilting point). However, the available moisture content within this pressure range varies from 25 cm per meter of soil depth (3 in/ft) for some silty loams, to less than 6 cm per meter of soil depth (0.75 in/ft) for some sandy soils. As a consequence, soil type can greatly influence irrigation management practices.

Soil at field capacity is a soil which is holding the moisture by capillarity only, which cannot be easily drained by the pull of gravity. When a plant has pulled enough of the moisture out of a soil, it begins to wilt because the soil cannot supply sufficient water to meet the plant needs. This is known as the wilting point. The amount of water between field capacity and the wilting point is referred to as total available moisture or total available water. The percentage of water at the permanent wilting point is usually less than half that at field capacity, but is still much greater than the water content of air dried soil (Figure 10).

When available soil moisture is below a 50 to 70 percent moisture depletion and approaching the permanent wilting point, the limited water supply plays an important part in retarding plant growth. When a plant becomes "stressed" due to deficiencies in soil water, several changes can occur in the physiological processes of the plant. If these stresses occur during a critical stage such as flowering or fruiting (critical stage(s) vary according to plant species), crop yields can be severely reduced. If the plant is stressed below the permanent wilting point, it will probably not recover.

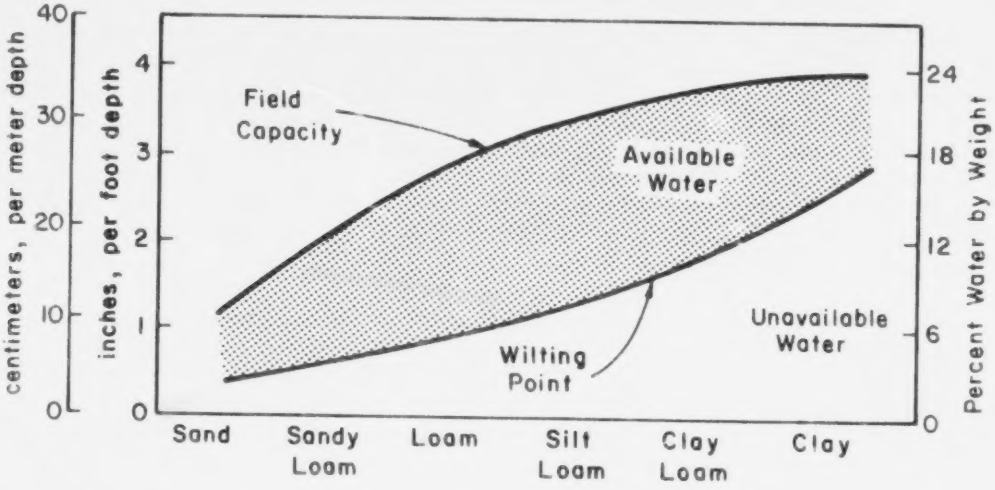


Figure 10. Typical water-holding capacities of different textured soils. [Note that maximum available water-holding capacity occurs in the silt loam (Adapted from USDA Yearbook, 1955)].

Soil Hydraulic Characteristics

A property of soils that is extremely important to irrigated agriculture is the rate of infiltration or the time rate at which water moves through the soil. It is influenced by the soil physical properties, the chemical properties which affect the physical properties of the soil and the hydraulic gradient. The configuration of the soil surface (i.e., furrows or borders), slope, roughness, and type of vegetative cover also influence infiltration. Whenever the surface configuration influences the rate of water entry into the soil, the term "intake rate" is used instead of "infiltration rate."

Infiltration rates vary from relatively high at the start of irrigation to a much lower value at the end. Infiltration rates also can vary throughout the irrigation season. Water applied to coarse or sandy soils will infiltrate rapidly, but water on very fine-textured clay soil may often stand for days, and the rate of evaporation can be higher than that for infiltration. The term cumulative infiltration or depth of application accounts for these time variations, and is used to define the total amount of water delivered to the root zone during an irrigation. The depth of application is dependent on length of the field, total time of application (total volume applied), and the volume rate of inflow.

Soil Physical Properties

The soil matrix serves several valuable functions, including serving as a foundation to hold the plants upright. It must furnish nutrients and provide a balance between areation and available moisture content.

Soil texture and structure influence the intermolecular forces and "suctions" of water in unsaturated soils. These forces can be quite substantial and include the capillarity and attractive forces resulting from close contact of soil particles. Soil texture and primarily soil structure greatly influence pore sizes, distribution of pore sizes, and the permeability of soils to air, water, and roots which is as important to crop growth as an adequate supply of nutrients. In fact, the entire soil-water-plant system is so interrelated that failure or lack of one component can cancel the combined benefits of the others.

The depth of soil is important because it establishes the amount of water and nutrients that can be stored, as well as the physical limits of the root zone. A uniform deep soil without confining substrata is necessary to have a well-drained soil. Shallow top soils can inhibit the rate and depth of root growth as well as subsurface drainage, if bedrock or hard pan conditions occur beneath the soil layer.

Proper irrigation practices are influenced by the degree of root proliferation since the water supply available to the plant is limited to the distribution and soil volume explored by the crop's root system. Different crops have different root growth patterns, hence, different moisture extraction patterns. Obviously, a shallow-rooted crop requires more frequent irrigations than a deep wide-rooted crop, providing both have the same soil conditions.

The depth of soil available for root exploration, even for a normally deep-rooted crop, may not always be evident from cursory observation of test holes. Marked changes in soil texture with depth warrant close inspection. For example, a sandy layer within the potential root zone of a clay soil may effectively impede root development by resisting water entry until the overlying soil is saturated. In this case, when irrigation water is applied in amounts necessary to replenish the potential root zone, the top layer becomes saturated and reduces soil aeration with consequent yield depression. Barriers to infiltration may also be caused by mineral deposits, such as calcium salts or "caliche", or by cultural practices such as plowing and soil compaction by farming operations which can form hardpans.

Good internal drainage of a soil profile is a necessary requirement for continued irrigated agriculture. If not naturally occurring, artificial means must be used such as mole drains or tile. In addition to soil layers or mineral deposits mentioned above, internal drainage might be hampered by a high water table. The presence of an impermeable layer or a shallow water table greatly affects the distribution of salts within the soil profile (Rhoades, 1974).

Soil Chemical Properties

Soils are generally classified by their chemical suitability for irrigation on the basis of their soluble salt concentration and the exchangeable sodium content. Both of these parameters depend on the soil moisture content. In soil analyses, the standard moisture content for these tests is the saturation moisture content. Valuable references in this area are Richards (1954) and Black et al. (1965).

Soluble salt concentrations are generally assessed by measuring the electrical conductivity of the saturation extract in units of millimhos/cm at 25 degrees C. Different crops are affected to different degrees by the soluble salt concentrations. These responses have been quantified in terms of electrical conductivity by the United States Department of Agriculture Salinity Laboratory in Agriculture Handbook No. 60 (Richards, 1954). These results are shown in Table 8.

TABLE 8. CROP YIELD RESPONSE AT VARIOUS LEVELS OF ELECTRICAL CONDUCTIVITY OF THE SATURATION EXTRACT OF SOILS (RICHARDS, 1954)

Electrical conductivity (mmho/cm @ 25°)[1]	Crop response
0 to 2	Salinity effect on yield negligible
0 to 4	Yield of very sensitive crops reduced
0 to 8	Yield of many crops reduced
0 to 16	Only tolerant crops yield satisfactorily
> 16	Only very tolerant crops yield satisfactorily

[1] Electrical conductivity is also measured in micromho/cm @ 25° C (μmho) which is 1/1000 of a millimho (mmho).

The standard method of assessing the effects of sodium is by determining the exchangeable sodium percentage (ESP), where

$$\text{ESP} = \frac{\text{Exchangeable sodium content}}{\text{Cation exchange capacity}} \times 100$$

However, the direct technique for determination of the ESP is somewhat time consuming and the easier, if slightly less reliable, sodium adsorption ratio (SAR) is usually determined to estimate the exchangeable sodium content (Withers and Vipond, 1974). The formula for the SAR is given by:

$$\text{SAR} = \frac{\text{Soluble sodium concentration}}{\sqrt{\dfrac{\text{Sol. calcium conc.} + \text{sol. magnesium conc.}}{2}}}$$

where the concentrations are expressed in millieqivalents per liter. An empirical relationship between the ESP and the SAR has been obtained (Richards, 1954) and is expressed by:

$$\mathrm{ESP} = \frac{100(-0.0126 + 0.01475\ \mathrm{SAR})}{1 + (-0.0126 + 0.01475\ \mathrm{SAR})}$$

If the ESP should exceed 15, the soils are classed as "sodic" and essentially unusable for most agricultural purposes.

Chemical properties of soils can greatly influence the irrigability of the soil by affecting the hydraulic characteristics and suitability of the soil for crop production. Soils having an excess of soluble salts are designated as saline soils, and, if the soil has an excess of exchangeable sodium, it is termed a sodic soil. The basis of the classification of these soils is given in Table 9. Sodic soils tend to have very poor soil structure due to swelling or dispersion properties that tend to reduce the range of pore sizes (Corey, 1977). This adversely affects the hydraulic properties of the soil. For example, hydraulic conductivity of a soil can change as much as three orders of magnitude when the sodium adsorption ratio is reduced from a value of 20 to 1, providing all other soil properties are constant (Dane, 1976).

TABLE 9. CLASSIFICATION OF SOILS BY THE SOLUBLE SALT CONTENT AND EXCHANGEABLE SODIUM PERCENTAGE (RICHARDS, 1954).

Soil	Electrical Conductivity of saturation extract (mmho/cm at 25°)	Exchangeable sodium percentage
Saline	>4	<15
Alkali (Sodic)	<4	>15
Saline Alkali	>4	>15

Excess soil salinity will delay or prevent crop germination and can substantially reduce the amount and rate of plant growth because of high osmotic pressures that develop between the soil-water solution and the plant. These pressures greatly impair the plant's ability to absorb water. The osmotic pressure correlates well with total dissolved solids and appears to be independent of the type of salts present because most soil solutions have sufficiently similar distributions of mono and divalent ions. In addition, some adverse effects due to salinity can include nutritional imbalances or toxicities caused by specific ions such as boron which can be toxic in very small quantities. In sufficient concentrations, even beneficial salts, such as potassium nitrate, can become toxic to plants.

In addition to the soil chemical characteristics mentioned above, the soil must also have an adequate supply of available plant nutrients.

Many chemical elements are essential for plant growth and are necessary to obtain large and satisfactory crop yields. These include calcium, iron, magnesium, nitrogen, potassium, phosphorus, sulfur, and many other trace elements depending on the type of crop. The availability of nutrients to the plant largely depends upon the moisture content of the soil.

Bacterial activity is also an important part of the soil-water-plant relationship since this action often converts nitrogen to a usable form. This is called nitrogen-fixation. Bacterial action also breaks down organic matter and converts other chemical compounds into forms usable by the plants. Soil moisture content, structure, aeration, and organic matter (carbon source) directly influence bacterial activity.

IRRIGATION WATER MANAGEMENT

Improved water management practices are needed to minimize diversions to new croplands due to limited water supplies. Future diversions to irrigated agriculture may have to be reduced to provide water supplies for new demands. Minimization of water quality degradation in receiving streams resulting from irrigated agriculture, and maximization of agricultural production on existing croplands must be achieved. The solutions are identical. Whatever goal is undertaken, better water management practices are mandatory.

Definition of an Irrigation System

An irrigation system can be subdivided into three major subsystems: (a) the water delivery subsystem; (b) the farm subsystem; and (c) the water removal subsystem. The water delivery subsystem can be subdivided further into two components including the transport of water and pollutants from the headwaters of the watershed to the section of the river where water is diverted to irrigated croplands, and the transport of water and pollutants from the river diversion works to the individual farm (Skogerboe and Law, 1971). This manual will only refer to the second portion of this delivery system. The farm subsystem begins at the point where water is delivered to the farm and continues to where water is removed from the farm. The farm subsystem is defined vertically as beginning at the ground surface and terminating at the bottom of the root zone. The water removal subsystem consists of surface runoff from the lower end of the farm and water moving below the root zone. These subsystems are illustrated in Figure 11.

Planning for Effective Water Management

The resource base for irrigated agriculture has not changed substantially since its inception thousands of years ago. Development of surface water irrigation in the West during the past hundred years has produced little incentive for any major innovation to improve efficiency in the use of water, which is a scarce resource. The provision of irrigation water in many areas has been considered a governmental or collective responsibility, and the direct charges made for water usually have not been high enough to encourage proper budgeting of water or other necessary improved irrigation methods. The custom of undercharging for water continues today;

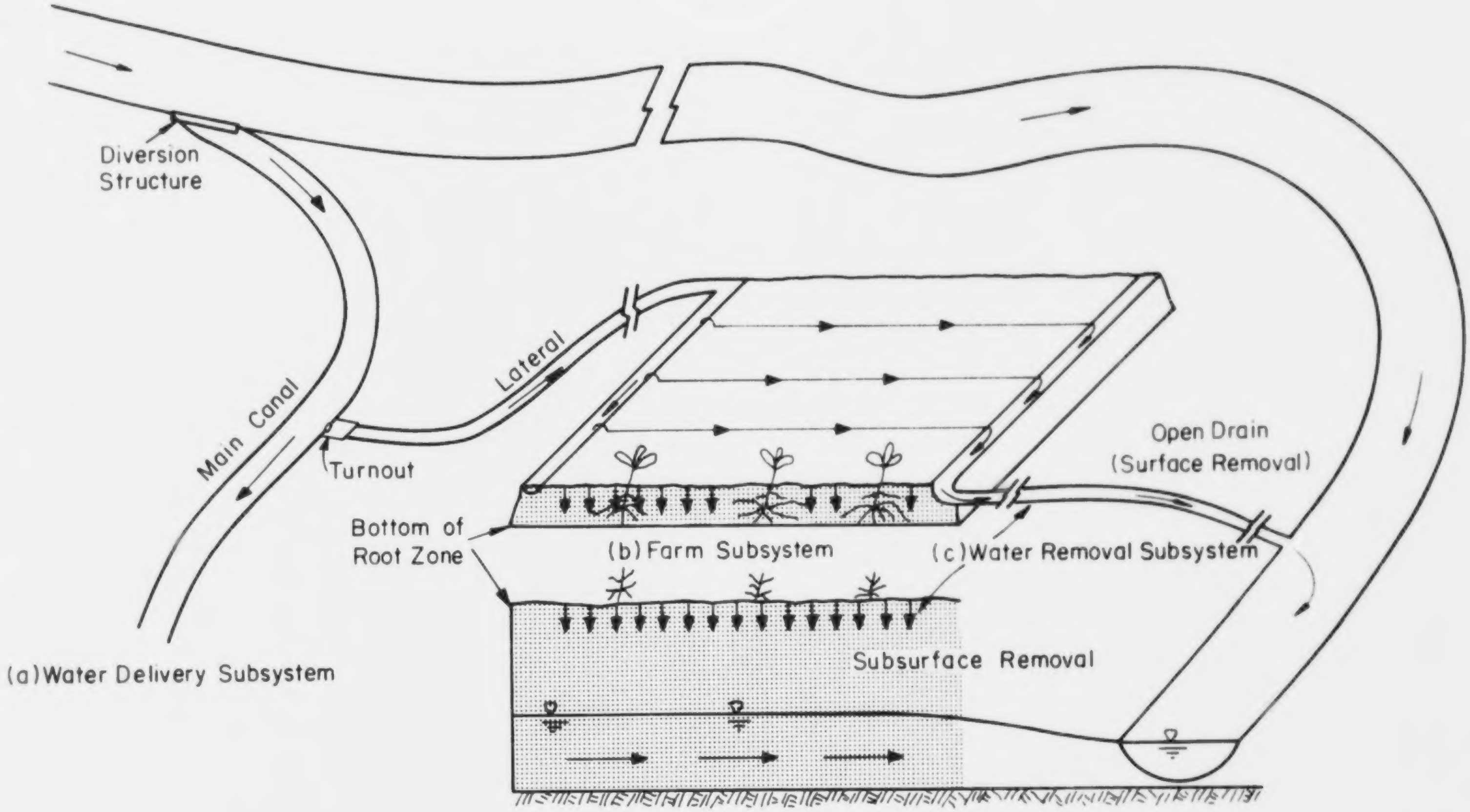

Diversion Structure
Main Canal
Turnout
Lateral
Bottom of Root Zone
(a)Water Delivery Subsystem
(b) Farm Subsystem
(c) Water Removal Subsystem
Open Drain
(Surface Removal)
Subsurface Removal

Figure 11. Water delivery, farm, and removal irrigation subsystems.

with only a few regions charging the farmers for the real cost of water. There are a few extremely water-scarce areas in the West where considerable ingenuity was applied to effectively utilize water supplies. Pumped water supplies do reflect the "true" cost of water and these areas are usually much more innovative and willing to accept new practices.

Aggravating this situation of so-called "cheap water" is the fact that development of irrigated agriculture in most places, even in the last few decades, has focused almost entirely upon the construction of water delivery subsystems. This preoccupation with installation of "hardware" results from a naive civil engineering approach to water management (Wiener, 1972). This approach is probably the greatest deterrent to improved water management in most irrigation systems today. This is especially true when other additional problems require attention such as the need for improved soil-plant-water management techniques, cultural practices, advisory services and input supply systems, administration of institutions, water laws, water quality, and many other factors that must fit together to form a most complex system. In irrigated agriculture, there is a wide gap that frequently exists between "hardware development" and the development of other requisites for increased agricultural production.

The approach that has been applied to irrigated agricultural development in the past is characterized by separating the development of water resources from the management aspects of water resource utilization. The record shows development being emphasized greatly while management is often neglected. This orthodox approach was used almost exclusively with reasonable success in the western United States. However, as the water resources become more fully utilized, necessity for meeting new water demands, along with physical, socio-economic, and political problems of water quality degradation, require rejection of many conventional guidelines from the past.

In contrast to the mere development of a water resources approach, the "management" approach attempts to achieve water development objectives by applying a variety of measures after studying the entire system, thereby attempting to modify the system to meet new and changing demands. Instead of constructing engineering structures to meet these new demands, focus should be on water resource management, with construction works considered only when necessary to meet water management objectives (Wiener, 1972). Unfortunately, in most cases, water management and the many disciplines required to produce efficient management are postponed until the post analysis of an engineering project which aggravates not only the advance of technology, but constrains or makes difficult the implementation of a variety of services requiring strong institutional measures.

Operation and Management of an Irrigation System

The "heart" of the whole irrigation system is the farm subsystem. The purpose of the irrigation system is to grow food. The connection between the food and the irrigation system is the root zone. The water delivery and water removal subsystems exist to support this "purpose." Proper operation and management of an irrigation system requires, first, that the farm subsystem be adequately designed, operated, and managed so the water delivery subsystem can be operated to provide proper quantities of water at the times required by the plants. The most important constraint in the operation process is the necessity to assure adequate drainage through the root zone in order to maintain a favorable root-zone salt balance and provide good aeration to enable continued agricultural productivity. At the same time, quantities of water moving below the root zone can result in waterlogging and salinity problems which can require expensive relief drainage facilities.

Farm Subsystem--

The most important irrigation variables in operating the farm subsystem are climate, water, soils, crops, topography, method of irrigation, and the skill of the irrigators. The interrelationships between these variables dictate the capability of the land resource for producing food and fiber. Frequently, in the arid West, water is the most limiting factor in agricultural production. The capability of the available water supplies from precipitation, surface runoff, and groundwater for plant production is highly dependent upon the efficiencies at which the water is used, which in turn is a function of both economic and institutional factors. Use of proper irrigation methods and practices are crucial for: (a) uniformly distributing the necessary moisture throughout the field; and (b) minimizing deep percolation losses so as not to aggravate problems in the water removal subsystem such as waterlogging and salinity, and yet retain fertilizer where it can be used by the plant.

Water Delivery Subsystem--

The crop water plus leaching requirements of each farm should dictate the operation of the water delivery subsystem. These water requirements determine the necessary quantities and timing of water deliveries at the farm inlets. The water delivery network must be capable of handling these farm water requirements.

One of the essential facilities for successfully operating an irrigation conveyance network is adequate flow measurement devices. Each field has a particular water requirement; the only means by which the proper amount of water can be delivered is by measuring the water at the farm inlet. The farmer cannot be expected to use good water management practices if the quantity of water being managed is unknown. Besides each farm inlet, a flow measurement structure should be provided at all division points in the water delivery subsystem to ensure equitable allocation of water among users. Water measurement is discussed in more detail in Section 8.

A major problem in the water delivery subsystem is the institutional framework controlling the operation of this portion of the irrigation system. Generally, operation of the conveyance facilities was not related to the requirements for sustaining long-term productive agriculture. In particular, institutional factors such as water laws and the existing water cost structures have constrained improved water management.

The primary requirement for sustaining an irrigation system is an institutional framework that is compatible with the operational requirements for the water delivery subsystem. The operational requirements, in turn, must be dictated by water requirements for each farm as well as constraints imposed by the water removal subsystem. Thus, even if all three components of the irrigation system are properly designed, lack of an adequate institutional framework for operating the system in accordance with good water management criteria will likely lead to either failure of the system or at least lower agricultural production levels.

The existing water rights system in the western United States is an example of an institutional constraint to improved water management practices. Water has been allocated to irrigated agriculture in the majority of the 17 western states under the doctrine of prior appropriation since the mid-1800's. The practice of granting water use on the basis of seniority has become institutionalized and very resistant to change. Water has been diverted for agriculture since the inception of the doctrine and often by the same conveyance and application practices employed when the right was initiated. Fear of loss of the right through nonuse compels water users to divert their full allotment so that change in irrigation water management practices will occur only if strong incentives are provided. The objective of the water right is satisfied once the water is applied. Water quality degradation sustained downstream from surface (tailwater) runoff or subsurface (seepage and deep percolation) return flows is of little concern to the appropriator. There are no water quality criteria associated with most of the prior appropriation laws. The water rights system is discussed in more detail later in this section.

Water Removal Subsystem--

The principal function of the water removal subsystem is to allow proper drainage below the root zone so adequate aeration and the leaching of salts from the root zone will occur. One of the most satisfactory mechanisms for minimizing drainage needs is proper operation of the water delivery subsystem. By appropriate operation, it is possible that a drainage problem will not occur.

Another important consideration in the water removal subsystem is water quality. If canal seepage and cropland deep percolation losses result in water quality degradation of the underlying groundwater supplies, then use of these supplies may become impaired. Also, return flows to the river may limit the usefulness of the river water to downstream users. Numerous examples of this situation can be cited throughout the West.

Administration of an Irrigation Subsystem--

The proper functioning of an irrigation system is dependent upon the institutional framework. This framework must be compatible with the design criteria used in constructing the system, and still provide flexibility to achieve improved water management as the need arises. Satisfying on-farm water management objectives cannot be achieved without controlling water deliveries, and administration of the irrigation system requires that satisfactory legal mechanisms exist to control water deliveries.

The provision of adequately trained personnel for the operation and maintenance of irrigation systems may be understood, but is difficult to accomplish. The focus must be on training not only the engineers and technicians, but those working in conjunction with the farmer. Although agricultural experiment stations exist, there are usually limitations in accomplishing on-farm improvements due to the few adequately trained farm-level advisors capable of applying research results to the farms.

WATER LAW

One of the most important factors of implementing technological change for salinity management in irrigated agriculture is the water rights held by farmers and irrigation companies and districts. This is due to the many organizations and mechanisms which have developed to control and administer these rights.

Water law in the United States is a federated system with a delineation of jurisdiction at the national and state levels. The nationwide federal water law is uniform with some regional flexibility. Each of the 50 states has adopted surface and groundwater laws that vary significantly. State water quality laws, on the other hand, are more uniform and generally follow the pattern set by the federal legislation of 1956 (P.L. 84-660), 1965 (P.L. 89-234), and 1972 (P.L. 92-500) and their respective amendments.

Federal Water Law

The federal government holds direct control of water rights by two primary means: (a) the holding of water rights on federal reclamation projects by the United States Bureau of Reclamation until the project reimbursement costs are paid; and (b) the Reservation Doctrine. The Reservation Doctrine is alleged to give the federal government power to reserve water on lands withdrawn from private purchase and lands designated for specific federal purposes, such as national parks, forests, recreational areas, wildlife refuges, oil shale reserves and hydro-power locations. The reservation extends to all present and future uses, is not lost through nonuse, and has a priority corresponding with the date of the legislation that withdrew these lands from other uses. This doctrine has been interpreted to include both surface and groundwaters (Radosevich and Daines, 1976). However, the validity and applicability of this doctrine has been severely curtailed by two recent Supreme Court decisions. Trelease (1971) presented detailed information regarding federal-state water relations in a report to the National Water Commission.

State Water Law

Surface water laws in the United States developed along two distinct philosophies that are generally consistent with the geographical and climatic characteristics of the individual state. In the eastern half of the country, and along the west coast, the Riparian Doctrine was adopted. The western half of the country, as a result of much trial, error and compromise, designed a water right system that is characteristic to arid lands and is broadly described as the Prior Appropriation Doctrine. These include: Montana, Idaho, Wyoming, Nevada, Utah, Colorado, Arizona, and New Mexico. On the other hand, California, Oregon, Washington, North and South Dakota, Nebraska, Kansas, Oklahoma, Texas, and Mississippi have spatially varied water availability; and consequently, adopted a mixed riparian and prior appropriation system. States not listed above have various forms of the riparian water law system.

Riparian Water Law--

The riparian water laws common to humid regions in the United States were patterned after the early common law of England. Under this English law, every landowner with property adjacent to a stream or body of water was entitled to use as much of this water as was desired, as long as it was not diminished in quality. The right to use the water was not a right for fixed quantity of flow or volume, but was dependent upon the extent of water-use development that had taken place. Generally, the water right was attached to the land that could not be separated.

As a result of the conflicts that arose when emerging industries, municipalities and agriculture in the United States began diverting water, the American Rule of Reasonable Use was established. Under this rule, riparian landowners can divert a "reasonable" amount of water with respect to all other riparians on the stream. In addition, nonriparian lands may, under certain conditions, make use of the available waters.

Prior Appropriation Water Law--

The Appropriation Doctrine is a water allocation system developed in response to the early gold and silver mining interests in the West. Miners recognized that the Riparian Doctrine was not workable under conditions they encountered. In response, they applied the same principles to their water as they did to their mines. That is, the first person to discover a mine was protected against later claimants. In terms of water, this was translated into the familiar quote of "first in time is first in right," or, in other words, the first person to use a specified amount of water acquired the right to its future beneficial, reasonable, and continuous use. Water supplies above the specified amount were free to be appropriated by other users.

One of the primary differences between the riparian and prior appropriation doctrines is that in the latter doctrine, the priority of right and not the equality of right is the basis for dividing water during periods of scarcity. There is no proration when water shortages occur. This means that all users are given a time priority by date. For example, the most recent water allocation granted is the first to be denied the right to divert water. From this it can be seen that the burden of shortages always falls on those allocated most recently, but does guarantee a dependable supply to those with senior rights. As a result, the economic value of water rights greatly depends upon the priority date and the source of supply in terms of dependability of flow.

In response to the concern that some users are more critical than others, states with various appropriation doctrines have adopted statutes that define "preferred uses." These designations allow a preferred use to condemn water, with compensation, from a nonpreferred or a "less" preferred use in times of shortages. This order of preference also serves as criteria for the allocating agency when several uses are competing for the same unappropriated water. Generally, the order of ranking for water use is domestic, agricultural, industrial, power, fish and wildlife, and recreation.

In existing irrigated areas, many of the appropriated water rights are dependent on return flows from the above lands. Any degradation of quality or quantity of these return flows can cause economic and agronomic hardship on the downstream users. Changes in irrigation practices, extensions of the irrigated acreage or water transfers that change the quantity and temporal distribution of the return flows can affect the value and use of downstream water rights. Changes in irrigation practices are usually permitted except for surface reuse systems where the size of the tailwater pond is controlled so that, in effect, it does not result in a storage right. Extending the irrigated acreage is not allowed, except where increases are with unappropriated water. The amount allowed to be transferred is usually limited only to the consumptive use. In any proposed change, it must be shown that no other appropriator would be hurt by these new practices or uses. Case studies and discussions on the legal interpretation of both water law doctrines can be found in Trelease (1967), Sax (1968), Radosevich and Hamburg (1971), and Radosevich and Allen (1975).

The existing water law systems in the western United States tend to act as an institutional constraint to good irrigation water management. Water rights are based on a rate of flow rather than a volume measurement, or consideration of the crop water requirements. Also, if an irrigator or irrigation district does not divert the total amount or rate of flow of the adjudicated water right, the undiverted portion of the right will be appropriated by other users through abandonment procedures. The full water right is usually diverted even though part of it is not needed, and the excess water is either returned unused to the stream or applied to the land.

If best management practices were implemented and the diversion requirements were reduced, under the existing laws this "excess" water would then go in order of priority to more junior appropriators up to the flow rate of their allocated water right. This water would not necessarily remain in the stream for fisheries enhancement or flow augmentation unless the junior appropriators were downstream, which is often not the case in the West. Since water would be available for more time during the irrigation season to these junior appropriators, the result may be increased pollution from their lands and the net effect on the stream would remain the same, even with best management practices under the existing water laws in these areas.

Groundwater Law--

In many areas of the United States, groundwater resources play an increasingly major role in agriculture, municipal and industrial uses. Since 1950 there has been an estimated 240 percent increase in the use of fresh groundwater supplies. In 1975, it was estimated that approximately 38 percent of the water withdrawn in the country came from groundwater sources (Murray and Reeves, 1977). Due to this rapid expansion in groundwater utilization, many state laws controlling its extraction and use have been enacted. These laws are at least as complex as the corresponding surface water laws. There are several legal approaches to this problem. Most of the western states have elected to adopt groundwater statutes similar in philosophy to the prior appropriation doctrine. This was necessary because surface and groundwater are often hydraulically interconnected, and withdrawals from one will affect the other. These laws generally permit the appropriation of groundwater for a beneficial use provided that the intended user complies with all the statutory requirements. It is the responsibility of the administrative officials to determine if groundwater exists and what adverse effects would occur if the application was approved. A more in-depth discussion on groundwater law is presented by Corker (1971).

SECTION 4

POTENTIAL TECHNOLOGICAL SOLUTIONS

All salinity problems result from both salt pickup and salt concentrating effects. No irrigated area contributes salts due to only one cause to the total exclusion of the other. The relative magnitude of these sources, however, does determine the emphasis of the salinity program to be implemented. In areas where salt concentration is the primary cause of increased salinity, the concentration of salinity in the subsurface return flows is usually approximately inversely proportional to quantity of deep percolation, except where chemical precipitation may be significant. Therefore, the emphasis of the best management practices is directed toward reducing the chemical concentration of the deep percolation by measures such as minimum leaching (USDA, Salinity Laboratory, 1977), phreatophyte control, growing more salt tolerant crops, land retirement, and collection and disposal or treatment (desalination) of the irrigation return flows.

For areas which primarily contribute salinity due to salt pickup, the emphasis of a salinity control program is to reduce the quantity of canal and lateral seepage and deep percolation losses. Best management practices will consist of canal and lateral lining to reduce seepage losses, along with minimizing deep percolation by improved on-farm water management practices such as installation of accurate flow measurement devices, irrigation scheduling, and more uniform water applications. For most areas, the salinity problems result from a combination of both salt concentration and salt pickup, which requires an integrated site-specific combination of the above types of strategies.

Achieving high irrigation efficiencies and other improved irrigation management practices are goals not only of water quality planners, but of individual irrigators and irrigation organizations as well. King (1973) and Willardson and Hanks (1976) discuss many of the effects of irrigation management on irrigation return flows. The technological solutions to salinity problems are often the solutions applicable to reducing agricultural energy consumption, achieving higher farm production and higher profits. In this section, potential technological solutions to the problems of salinity are discussed.

The collection and treatment or disposal of irrigation return flows are usually straightforward engineering problems and are summarized near the conclusion of this section. For the most part, increasing the efficiency of irrigation is a complex task. Improving physical aspects of the irrigation system, including structural rehabilitation and redesign and instituting better management practices for the operation of the system by irrigation scheduling, call periods, and limiting wastes, must be considered in any program for improving the efficiencies of irrigation.

Irrigation is an integral part of the larger hydrologic system encompassed by a river basin or watershed. Salinity control measures must be compatible with the objectives for water resource management and development in the total system. These can be logically divided into measures aimed at improving the operation and management of the three major subsystems within the irrigated systems: (a) the water delivery subsystem; (b) the farm subsystem; and (c) the water removal subsystem.

IMPROVING THE WATER DELIVERY SUBSYSTEM

The conveyance of water from the source of supply, such as a stream, reservoir, or groundwater, to the inlet of the irrigated field boundaries constitutes the water delivery subsystem. Salinity problems associated with this subsystem are primarily a result of seepage from the channels into the soil and substrata where salts are picked up and transported to the groundwater, or back to the river or stream. Seepage water from the delivery subsystem may be lost to nonbeneficial consumptive use by phreatophytes and direct evaporation from high water table areas resulting in salt concentrating effects. In open conveyances, evaporation from the water surfaces also concentrate salinity; however, these losses are generally insignificant.

The operation of the water delivery subsystem can also be expected to indirectly affect water utilization in both the farm and water removal subsystems. Careful management and accurate measurement and allocation of water results in higher on-farm irrigation efficiencies. Properly maintained and operated conveyances reduce the water removal subsystem requirements since less water is spilled or lost through seepage. Improvements in the water delivery subsystem affecting the quantity and quality of irrigation return flows fall into the following categories: (a) seepage control; and (b) systems management and operation which includes flow measurement and control.

Seepage Control

Many unlined canals, ditches, laterals, and water courses traverse long distances between the point of diversion and the farm. Where soils are well structured and permeable, seepage losses may be considerable. Traditionally, reaches with high seepage loss have been lined with a variety of alternative materials such as concrete, asphalt, bentonite, compacted earth, and plastics to prevent seepage with the economic justification based on the value of the water saved. Converting to a closed conduit of concrete, asbestos-cement (A-C) or plastic is an effective alternative that offers advantages of better trafficability, reduced evaporation, maintenance of pressure due to gravity, and aesthetics. The salt pickup contribution from conveyance seepage can often exceed that leached from the irrigated land which is necessary to maintain a salt balance in the root zone. The time required to transport these residual salts to receiving waters depends upon the distance traveled and the hydraulic properties of the aquifer. The time is, however, usually sufficient for the seepage flows to reach chemical equilibrium with the soils and/or geologic substrata. In addition to the quantity of water saved, conveyance linings ordinarily eliminate the salt loading impacts. Improved water quality may be another benefit claimed in the economic justification for seepage controls if soils along the routes traversed by the irrigation channels are high in residual salts.

Costs of conveyance channel lining vary with the square root of the channel capacity, so unit costs diminish with increased scale of construction. Seepage rates per unit of channel area, on the other hand, tend to be higher with smaller-sized channels because of less maintenance, greater depths to a water table, and larger ratios of wetted perimeter to discharge capacity. In that event, the cost effectiveness of lining each portion of the water delivery subsystem is not readily apparent and should be evaluated further.

Flow Measurement and Control

The purposes of flow measurement and control in irrigation systems are to ensure an adequate application of water to the croplands and to prevent unnecessary and wasteful diversions, thereby ensuring an equitable water allocation. Unfortunately, irrigators often understand less about the measurement of their water than any other aspect of irrigation they handle.

Water control in the absence of flow measurement is very seldom adequate to achieve irrigation efficiencies that can combat water pollution problems, including salinity, resulting from irrigation return flows. In many instances, managers and water masters of irrigation companies and districts tend to deliver excess water to individual irrigated subunits in order to maintain or improve personal relations with the irrigators. Irrigators utilize these excess flows to ensure that no portion of their fields are underirrigated, ostensibly to prevent crop yield reductions. At the same time, most of these fields are overirrigated, which not only aggravates the salinity problem, but recent research shows that overirrigation will also reduce crop yields by decreased nutrient availability and, in extreme cases, by poor aeration. Inevitably, poor water management leads to inefficiencies, reduced yields, and subsequently, to salinity problems, both locally and downstream. The problems, however, are amenable to implementation of effective flow measuring and water control devices combined with improved irrigation practices on the croplands.

Water measurement structures are commercially and readily available to farmers, water masters, or any interested individual for almost any field condition. However, without correct installation and proper maintenance, most water measurement structures will indicate incorrect discharge measurements. Taking into account the conditions, the following criteria for selecting a flow measuring device should be considered:

1. Discharge should be read directly rather than requiring use of conversion tables or calculations.

2. Structures should be standardized, inexpensive, and easy to fabricate and install.

3. Structures should be hydraulically efficient (low hydraulic energy losses), self-cleaning, and easily maintained.

It is also desirable that they be volumetrically cumulative. Flow measurement structures or devices fall into three general classifications; (a) flumes, such as Parshall flumes, trapezoidal flumes, Cutthroat flumes, and H-Type flumes; (b) weirs; and (c) orifices. These are discussed in more detail in Section 8.

Flumes involve width constrictions for use in open channels where insufficient head is available to operate higher head loss structures such as weirs. While most of the commonly used flumes noted above are usually operated as critical depth or free flow devices, recently many have been calibrated for the subcritical or submerged flow regime.

In order to control the flow of water in canals or ditches, structures referred to as checks and drops are used. These structures specifically control the slope and elevation of water surfaces and are critical in dividing the water, as well as distributing water to each field. Other control structures include culverts and field inlet devices.

A check structure is used to maintain or increase water surface elevations in open channels and should be designed to allow the flow needed downstream to pass over or through the structure while maintaining a constant upstream depth. In that case, the check structure acts similar to an overflow weir, or an orifice, or a combination of both. Among the basic criteria for designing a check is the necessary height to maintain sufficient water surface elevation for distribution of the water, and a means of energy dissipation to prevent erosion downstream.

Drop structures are usually provided in gully control and for changing steep slopes to flatter ones. This change is usually facilitated by vertical or inclined drops and an energy dissipating structure. The purpose of drops in irrigation systems is to prevent erosion. In many, if not most installations, drops are used in conjunction with checks and dividers to control flows to other points in the system.

Numerous culverts are found in irrigation conveyance and distribution systems, as well as in farm head ditches and at points of tailwater runoff from croplands. They are commonly placed through canal banks to divert water into laterals. Rather than constructing small bridges, culverts are frequently placed in the channel to allow vehicles such as farm machinery to cross the channel. Because culverts may constrict flow, they also may function as flow measuring devices. Culverts often constrain operation of the system because of flow capacity restrictions.

Canal Management and Operation

The degradation of water quality associated with the irrigation of agricultural lands is often most economically controlled on croplands where the water is applied. This requires reevaluation of the presently employed irrigation practices. Extensive research in the related fields of agronomy and irrigation has made available information that serves as a technical basis for modifying existing irrigation methods. While the primary function of an irrigation system is to apply water on the farm, the primary responsibility for control lies with the operation of the conveyance and distribution system. An important part of water management practices needing improvement is methods used to operate the canals.

When the water quality aspects of irrigation are considered in planning improved canal systems, quite often radically different alternative canal management and operation practices are compared with existing ones. The essential function of the conveyances system is to provide water deliveries in sufficient amounts when requested. While these criteria are important when considering water quality, the methods are somewhat different in that it is important to deliver only the "required or sufficient" amounts of water, rather than to deliver "excessive" amounts of water to the farmer's turnout. This objective is no different when crop yields rather than water quality is the objective. However, changes that are necessary for water quality improvement may place severe restrictions upon present canal operation policies that require new feasible alternatives be developed for operating these systems.

Many kinds of canal management schemes are used due to each state's variations and interpretations of water rights and their diverse physical settings. To outline all the solutions that can improve management and operation of canals for water quality improvement would be difficult. To significantly alleviate water quality degradation, including salinity, from irrigated agriculture requires, in almost every case, a stronger capability for controlling water deliveries. An expedient first step to strengthen water control is to improve the physical facilities and operational policies of the canal system. Some important facets of water delivery subsystem management and operation are described below.

Call Periods--

A very effective means for increasing irrigation efficiencies is to establish a "water demand" delivery subsystem. Since demand usually cannot be satisfied instantaneously, the canal officials usually require a "call period." A call period is the minimum length of time that an irrigator is expected to place an order with the canal operator for a specified quantity of water prior to the next irrigation. The minimum length of time for the call period is dependent upon the response time of the particular water delivery subsystem to any changes in flow conditions. This practice allows water masters and ditch riders to plan in advance the regulation of the canal. This information is essential to operate the canals in an optimal manner since it allows the ditch riders to coordinate the internal water management of the water delivery subsystem with the main diversion.

Call periods facilitate increased on-farm irrigation efficiencies by encouraging farmers to spend more time planning irrigations, thereby making better use of the water. Many canal systems in operation today do not attempt to manage deliveries to the farmers beyond assuring that each irrigator has an equitable share. For example, some irrigation systems deliver water to a farmer on a periodic rotation basis, or each irrigator gets a certain percentage of the diversion. These conditions are prevalent in canal systems depending on direct diversions from fluctuating rivers or streams, necessitated by the high flows in the spring and low flows in the late summer. From a water quality management standpoint, these conditions promote wasteful use of water during high flow periods and result in water shortages during low flows, either can reduce crop yields. The irrigators on fixed rotation water deliveries must apply the water when it comes, whether it is needed or not, resulting in overirrigation during times when irrigation water supplies exceed the "water demand" of the crops.

Another important aspect of instituting call periods is the scheduling of canal maintenance work. This often requires a period of discontinued canal operation, during times when water demands are minimal, such as during the late maturity or harvesting of a major crop in the area. These considerations are important to farmers whose crop yields can be severely damaged if they cannot get water during critical growth periods. Often, only a one-or-two-day period is necessary for completion of maintenance work, and by knowing the irrigating schedules of the farmers, canal shut-off periods can be more easily scheduled.

Scheduling Water Deliveries--

Recent advances in the development of predictive evapotranspiration models provide an important water management methodology. Irrigation scheduling services combine meteorological data and soil moisture levels to forecast future irrigations, both in terms of the depths of water application and the timing of the irrigations. Almost all recent research in this important area has been performed by governmental agencies, but some studies have been completed by private commercial groups who provide irrigation scheduling services for farmers. Canal companies and irrigation districts are among the parties who should be interested in providing at least part of this information to the irrigators they serve. Most of the existing commercial services combine pesticide and fertilizer scheduling along with irrigation scheduling.

The importance of canal companies and irrigation districts being involved with irrigation scheduling cannot be over emphasized. Canal operators generally have better relations with farmers since they deal in the allocation and delivery of water. Also, the canal system can benefit by having water demand forecasts available. In an efficiently operated delivery system, it is essential that irrigators improve the operational practices by providing continual feedback to the canal operators.

Canal Maintenance

Inadequately maintained canals add to water quality degradation in rivers and streams that receive irrigation return flows. The effects of poor maintenance are often visually apparent in the irrigation channels, and at the various diversion and control structures located along the water delivery subsystem. Keeping irrigation canals in good condition must be accomplished so adequate water supplies can be made available to farms when required. Canal cross-sections must be kept free of silt deposits or protected from scour. Aquatic vegetation, in and along canals, needs to be controlled periodically to maintain the canal capacity, reduce evapotranspiration losses, and prevent clogging at control structures. Canal banks must be repaired when damaged by burrowing rodents or when breaks occur. Structures employed in canal systems must also be properly maintained against leakage, settling, or general wear. Because many irrigation projects have more than adequate water supplies, there has been little initiative to implement effective maintenance programs unless serious drainage problems or frequent canal failures occur. The water quality detriments caused by canals in poor condition requires improved maintenance programs.

Seepage Losses--

When aquatic vegetation is not prevented, the canals must be operated at higher water surface elevations, even during low demand periods. The increased wetted perimeters are accompanied by higher seepage rates, resulting in increased water quality deterioration. Dilapidated and leaky control structures allow water to move into unused ditches or wasteways where further additions to the groundwater occur. If bank vegetation becomes excessive, evapotranspiration losses in a canal section may become significant.

Good water delivery characteristics cannot be continued when weeds, moss, sediment, and leakage develop, or when linings and control structures are in disrepair. These conditions cause wide fluctuations in water levels throughout the canal length, which makes it almost impossible for farmers to apply water uniformly. Without workable canal systems, water management and thus water quality management cannot be successful.

Managing System Storage--

In well-managed irrigation systems, water storage in internal regulating reservoirs, if available, and the storage capacity of the canals provide operational flexibility and more efficient water use. Water storage, however, should be minimized in order to keep seepage and evaporation losses as small as possible. One of the common facets in canal operation is the "checking" of flows to raise the water elevation to provide adequate head on the canal turnout. To accomplish this, a considerable quantity of water may be needed as dead storage. Seepage rates, as well as additional water used by weeds along the canal bank, are increased. In many cases, when the irrigator concludes an irrigation, it is necessary to dump the dead storage into wasteways since the next irrigator downstream may not be able to handle the large surge of water that would develop. A feasible alternative would be to let the next downstream irrigator draw from the upstream storage shortly in advance of the conclusion of an irrigation; thereby utilizing the dead storage water along the system. Another effective alternative is to provide a limited storage capacity along a canal to collect and regulate waste flows. The ability to minimize seepage and aquatic weed effects in a canal system requires a high level of management and the lining of canal and storage facilities.

Storage within the canal system can be beneficially minimized in areas where canal diversions are received from reservoirs that serve to reduce fluctuations in the river and stream discharges. If water storage is available throughout the river basin, it is profitable for water users to store water high in the basin so evaporation losses are reduced, and flexibility in diversions is increased. In arid river basins, such as the Colorado River Basin, water quality is significantly aggravated by the concentrating effects of evaporation from the large storage reservoirs located in the lower reaches of the river.

Managing Waste Water--

Seasonally, many irrigation systems have a larger volume of water available than is necessary to adequately supply crop demands. When this happens, water management is often lax and water quality problems can occur. One of the undesirable practices often found in these systems is regulation of canal capacities by spilling the surplus water supplies rather than regulating the diversions at the river or reservoir. For example, in canals that are relatively long, because of the slow response time, it is common to operate the canals at capacity at all times, with unneeded water spilled into wasteways. Usually, canal flows must be controlled at several locations along the canal. Spillage often adds to the water quality deterioration in the rivers and streams to which the flow returns, mostly as a result of soil erosion and salt concentrating effects. Wasteways tend to be neglected; consequently, they usually nourish large populations of phreatophytes. In addition, water table elevations in the vicinity may be lower than water in the wasteway, resulting in additional seepage to underlying groundwater aquifers in the area. Where it is necessary to reduce groundwater flows, canal spillage is an undesirable water management practice from a water quality standpoint. Under improved operating conditions, this practice is usually eliminated because it wastes water that can be more beneficially used elsewhere.

IMPROVING THE FARM SUBSYSTEM

The most significant improvements to reduce water diversions and control waterlogging and salinity problems potentially come from improved on-farm water management. This is particularly true for areas containing large quantities of naturally occurring salts in the soil profile. Poor irrigation practices on the farm are the primary cause of excessive water diversions, as well as being the primary source of irrigation return flow quality problems.

Cultural Practices

When the soils to be irrigated are finely textured with low infiltration rates and low permeability, and the water supply delivered to the farm is saline, cultural practices such as tillage and planting are extremely significant if crops are to be grown successfully. This situation is further aggravated in irrigated areas having high summer temperatures. Under these conditions, the management alternatives include one or more of the following: (a) planting more salt tolerant plants, which are usually lower in cash value; (b) using special soil tillage practices, which may cost more; (c) leaching during the off-season; (d) leaching the field one year and planting a crop the next; (e) preparing the seedbed more carefully; (f) planning for proper location and accurate placement of seed; and (g) controlling the timing and amount of water application. Usually, these problems must be faced in the lower regions of a river basin where accumulative effects of upstream water quality degradation, along with having finer "heavy" soils, create difficult management decisions.

Generally, the deeper water stored in the soil is removed more slowly by evapotranspiration because the roots of most crops are more profuse near the upper portion of the root-zone profile. Soil structure, texture, and stratification primarily control the distribution of water storage in the soil. In extreme cases, deep tillage may be required to permit greater water storage capacity, as well as deeper root penetration into less permeable soil layers. At the same time, excessive or unnecessary tillage can be detrimental to stored soil water, increasing evaporative losses at times when the crop needs moisture the most, while reducing soil porosity and aeration. Therefore, cultural practices can play a significant role in overall farm water management.

Irrigation Scheduling

Many studies show that in irrigated areas the amount of water applied is often unrelated to the amount needed by the crop at that time. Usually, when the farmer finds the field is dry, irrigation will be initiated. The irrigation application, however, may be more than is required by the crop. A twofold problem results. If the plant was stressed, the potential yield probably has been diminished. The second problem is due to more water being applied than necessary. In extreme cases, this might lead to reduced aeration of the soil, loss of fertilizer (nitrogen), and reduced crop yields.

The purpose of computerized irrigation scheduling is to advise a farmer when to irrigate and how much water should be used (Jensen, 1969; Jensen, et al., 1970; and Jensen, 1975). A farmer may rely on visual indications of crop response to decide when to irrigate, or the farmer may irrigate on a fixed water rotation arrangement dictated by the calendar. Irrigation scheduling is geared towards taking soil moisture measurements and computing potential consumptive use for the crops being grown. The scheduling process then determines when to irrigate and the quantity of water to be applied. The collection of climatic data and the calculation and measurement of consumptive use are discussed in Section 8.

Irrigation scheduling relies upon two primary variables, evapotranspiration and available root-zone soil moisture. Field capacity and wilting point for the particular soils in any field must be determined. More importantly, depending on the irrigation method used, infiltration characteristics of the soils must be measured. Only by knowing how soil intake rates change with time during a single irrigation, as well as throughout the irrigation season, can meaningful predictions be made of: (a) the quantity of water that should be delivered at the farm inlet for each irrigation; and (b) the effect of modifying deep percolation losses. With good climatic and soils data, accurate predictions of the next irrigation date and the quantity of irrigation water to be applied can be made.

Results from irrigation scheduling are extremely promising and farmers are realizing significant benefits. Yields have increased since water was applied when needed rather than after the crops were stressed, or because excess water was applied by irrigating too early. Presently, irrigation scheduling has not resulted in reduction in total diverted water, although it would seem likely that a decrease in water diversions would occur with time as farmers gain more knowledge of what is occurring in the soil profile. Another benefit to farmers from scheduling is the capacity to anticipate dates when irrigation is to occur. This allows farmers to schedule the irrigation and to more effectively schedule other duties that must be performed on the farm.

Results of studies by Skogerboe et al. (1974a) indicate that irrigation scheduling programs have limited effectiveness for controlling salinity unless scheduling is accompanied by flow measurements at all major division points, farm inlets, and field tailwater exits. It is necessary for canal companies, irrigation districts, or government agencies to assume an expanding role in delivery of the water. These studies show that scheduling is a necessary, but not sufficient way to achieve improved irrigation. The real strides in reducing salt pickup resulting from overirrigation will come from irrigation scheduling in conjunction with improved on-farm irrigation practices. In fact, irrigation scheduling cannot be effectively accomplished without efficient irrigation systems unless the distribution of water and thereby the amount of infiltration is known.

Structural Rehabilitation and Replacement

If the problems of on-farm water management are properly conceptualized, the structural remedies to a salinity problem evolve into one or two alternatives:

1. On-farm conveyance networks should be lined or replaced with pipeline to prevent seepage; and

2. The uniformity of water application should be increased by altering irrigation practices or converting to more effective irrigation methods.

On-Farm Seepage Control--

Many farmers have lined their farm conveyance networks to reduce seepage, maintenance and labor. The most common lining methods include a concrete slipform lining, buried plastic membrane, compacted earth, or converting the ditches to plastic, concrete, or aluminum pipelines. These alternatives are relatively inexpensive and are accepted methods for improving on-farm water management. In order for the irrigator to operate his system effectively, flow measurement devices must be located so inflows to each field are known.

Improving Water Application Uniformity--

To adequately irrigate the least watered areas in a field without overirrigating other parts, uniformity of the application should be maximized. Since different irrigation methods have different uniformity problems, it is useful to segregate this explanation into the following irrigation methods: (a) surface irrigation; (b) sprinkler irrigation; and (c) trickle irrigation.

Surface irrigation--The predominant form of surface irrigation in the western United States is furrow irrigation. Other methods include border and basin irrigation which are not specifically discussed in this manual. Most surface irrigation is applied to relatively "tight" soils and on comparatively flat slopes, usually less than 1 to 1.5 percent. Infiltration in most soils generally follows an exponential function decaying with time. Since the water is conveyed over the surface of the soil in any surface irrigation method, the uniformity of water application is maximized when the "intake opportunity time" at both ends of the field are equal (Figure 12). Because of the time necessary for the conveyance of water from the head end to the tail end of the field, opportunity for times of equal intake along the field is not completely possible. If the slope is uniform and the runoff unrestricted, the least watered area of the field is usually at the lower end. Under existing surface irrigation management practices, the maximum irrigation efficiency which is acceptable to the farmer occurs when the moisture deficit in the least watered area is refilled. This concept is illustrated in Figure 13.

There are two wastes that usually occur as a result of surface irrigation; namely, water percolating below the root zone (deep percolation losses) and runoff from the lower end of the field (tailwater runoff). Efforts to reduce one type of waste water versus another can be competitive. For example, measures to minimize runoff will often increase deep percolation with the reverse also true. Since salinity is directly associated with deep percolation, local improvement programs will cause high runoff if not coupled with some system modification. In some irrigated areas, erosion is a major problem and reducing tailwater runoff would be the highest priority for alleviating water quality degradation.

Surface irrigation uniformity and efficiency can be substantially improved by three alternatives. First, irrigation scheduling should always be based on sampling at the least watered area of the field so the minimal intake opportunity time or irrigation set can be determined. The flow in the furrow or the unit flow in a border or basin should be adjusted so the time required for the flow to advance to the end of the field is about 25 percent of the minimal intake opportunity time, assuming a uniform slope. If these practices are implemented and adhered to strictly, deep percolation volumes could be cut up to 50 percent. Individual field length and discharge can usually be adjusted to satisfy these criteria.

The second method for improving surface irrigation uniformities and efficiencies is applicable primarily to furrow irrigation. Under this method, the head ditch is sufficiently automated so a large "wetting" furrow stream is introduced to quickly advance the flow down the furrow. The flow

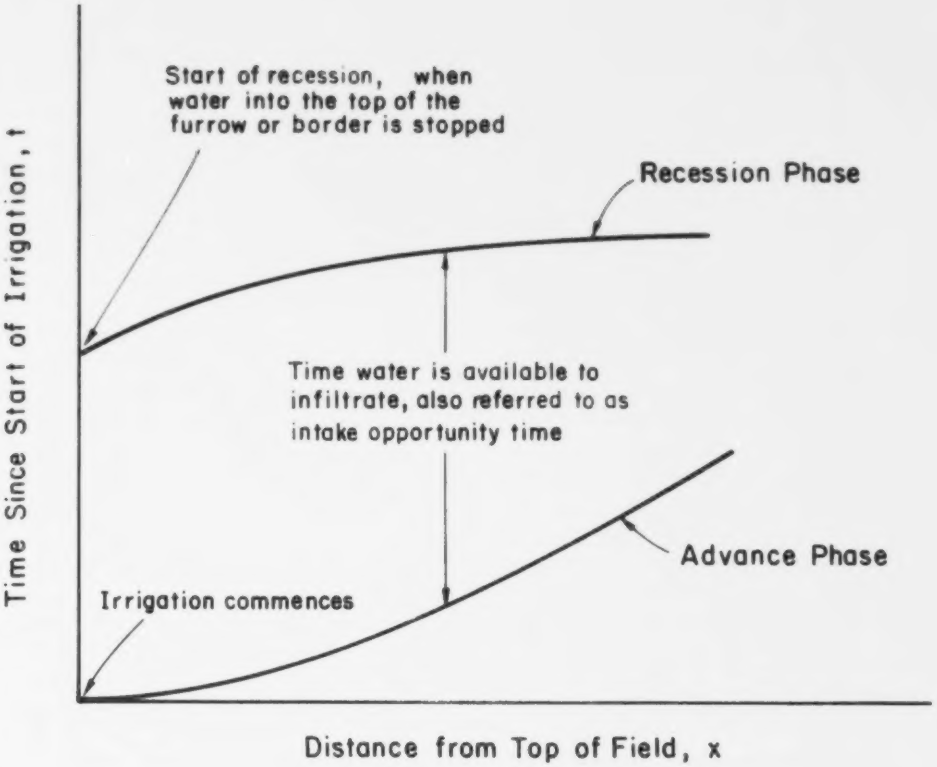

Start of recession, when water into the top of the furrow or border is stopped
Recession Phase
Time water is available to infiltrate, also referred to as intake opportunity time
Advance Phase
Irrigation commences
Time Since Start of Irrigation, t
Distance from Top of Field, x

Figure 12. Schematic representation of intake opportunity time and typical advance and recession curves for surface irrigation.

is then "cutback" to a "soaking" flow rate to finish the irrigation. This methodology, illustrated in Figure 14, has been utilized with good results in numerous areas. It has about the same unit salinity control cost-effectiveness as lining the on-farm conveyance channels. In addition to substantial labor savings due to inexpensive automation, cutback irrigation has a notable advantage over simply improving the existing system in that field tailwater runoff is also greatly reduced. This method is applicable only if sufficient cross slope is available.

The final alternative for improving surface irrigation uniformities is a tailwater reuse system which utilizes large flow rates without causing soil erosion. The system collects the tailwater runoff in a small reservoir, and then pumps this water back to the head of the field for reuse (Figure 15) This technology represents a very efficient surface irrigation system when operating with respect to a known soil moisture deficit. This design completely eliminates on-farm surface wastes. Another efficient surface irrigation method used in the southwestern United States is level borders that may have application efficiencies greater than 90 percent.

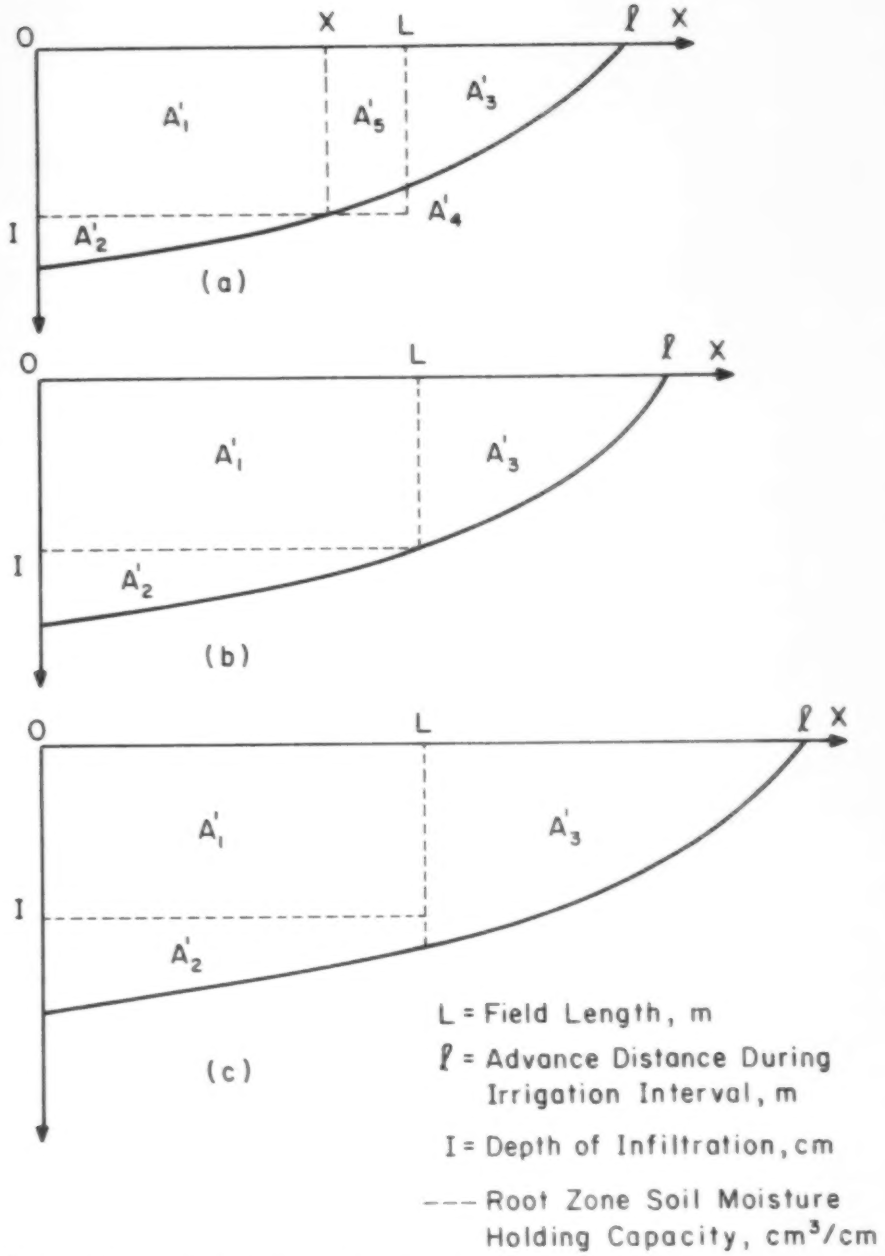

O
X
L
ℓ
X
A'1
A'5
A'3
A'4
I
A'2
(a)
O
L
ℓ
X
A'1
A'3
I
A'2
(b)
O
L
ℓ
X
A'1
A'3
I
A'2
(c)
L = Field Length, m
ℓ = Advance Distance During Irrigation Interval, m
I = Depth of Infiltration, cm
--- Root Zone Soil Moisture Holding Capacity, cm³/cm

Figure 13. Definition sketch of surface irrigation application uniformity for (a) the case where part of the field is underirrigated, (b) the case of zero underirrigation, and (c) conditions of significant overirrigation (Gerards, 1978).

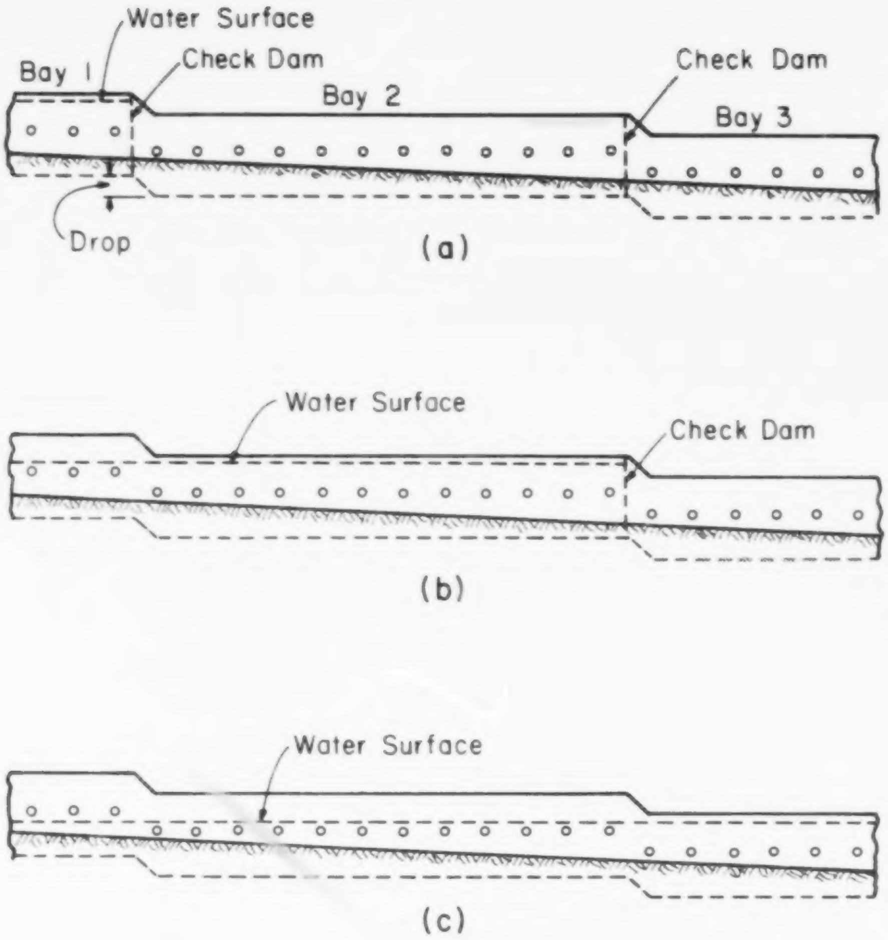

Water Surface
Bay 1
Check Dam
Bay 2
Check Dam
Bay 3
Drop
(a)
Water Surface
Check Dam
(b)
Water Surface
(c)

Figure 14. Elevation drawing of cutback furrow irrigation system with spiles in the ditch sidewall. In (a) bay 1 is delivering the initial furrow flow. In (b) the check dam has been removed from bay 1; bay 2 is delivering the initial furrow flow and bay 1 is delivering the cutback flow. In (c) the check dam has been removed from bay 2; bay 3 is delivering the initial furrow flow; bay 2 is delivering the cutback furrow flow and bay 1 is shutoff (Garton, 1966).

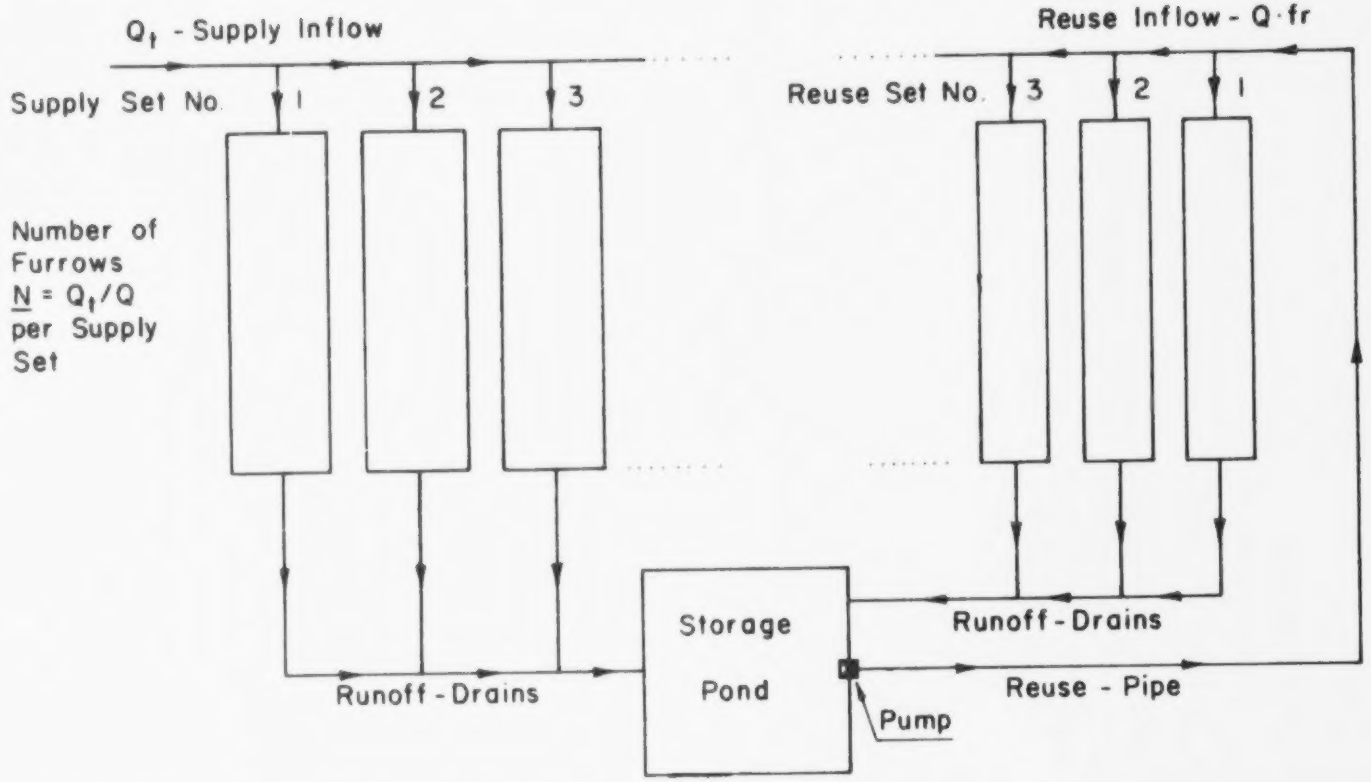

Q_t - Supply Inflow
Supply Set No.
1
2
3
Number of Furrows $\underline{N} = Q_t/Q$ per Supply Set
Runoff - Drains
Storage Pond
Pump
Reuse Inflow - Q·fr
Reuse Set No.
3
2
1
Runoff - Drains
Reuse - Pipe

Figure 15. Schematic illustration of a tailwater recovery and reuse system for surface irrigation (Gerards, 1978).

Sprinkler Irrigation--A conversion by farmers from surface methods to sprinkler irrigation could be highly beneficial in terms of more efficient water use. Sprinkler irrigation, properly designed, installed and operated, is advantageous to both water quantity and quality. Uniform water application is generally possible on various types of soils, thereby minimizing deep percolation losses; and, of course, no tailwater runoff should result. The division and shape of lands in many of the irrigated valleys of the West are such that the most effective sprinkler system would be the familiar mobile side-roll, center-pivot, or other movable systems. In orchards, tow-line or solid-set sprinklers are more advantageous.

Apart from the water quality benefits, there are many other advantages to farmers in converting to sprinklers. The labor savings are particularly noticeable in comparison with surface irrigation methods. With permanent set systems, labor is negligible and the systems are easily adapted to automation and other water application purposes such as frost control and cooling.

Besides reducing nutrient losses as a result of lessening deep percolation, further fertilizer economics can be achieved by the use of sprinkler systems to apply fertilizers during the time(s) required by the plant. Certain water soluble fertilizers can be applied through the sprinklers. The timing and amount of application can be controlled more nearly to meet the needs of the plant. The ability to schedule fertilizer applications to plant needs, rather than to cultural operations, reduces the opportunity for leaching nutrients below the root zone. This does have disadvantages; for example, if an unusually large rain should satisfy the plant needs, the system may have to be operated in order to meet the fertilizer needs. The excess water then leaches some of the nutrients, negating the benefits of the system.

Water soluble herbicides and insecticides can also be applied through sprinklers. The amount of water applied by a sprinkler irrigation system can be accurately controlled to meet the needs of the crop. Small depths of water can be applied early in the season when crop water requirements are low because of mild weather, or because the roots of the plants are not yet developed. Being able to apply small depths of water avoids excessive deep percolation losses that commonly occur under surface irrigation methods during early season irrigations.

Sprinklers, like most physical systems, do have disadvantages. Damage to some crops has been observed when poor quality irrigation water has been applied to the foliage by sprinklers (Harding et al., 1958). Poor quality water can leave undesirable deposits or coloring on the leaves or fruit of the crop. Sprinklers are also capable of increasing the incidence of certain crop diseases, such as fire blight in pears, fungi or foliar bacteria. A major disadvantage of sprinklers is the relatively high capital cost, especially for solid-set systems in comparison to surface irrigation methods. When gravity cannot supply sufficient head to operate the system, sprinklers can require large amounts of energy when the water has to be pumped to supply the necessary pressure. In many cases, it is often more economical to use conventional surface irrigation systems. The advantages and disadvantages of sprinkler systems must be assessed economically with other irrigation methods. Likewise, individual types of sprinkler systems should be compared to one another.

Trickle Irrigation--Trickle or drip irrigation is a recently developed irrigation method and appears to be particularly suitable for orchard or other high value crops. This method of irrigation gained attention during recent years because of the potential for increasing yields while decreasing water requirements and labor. The concept of trickle irrigation is to continuously provide the plant with the optimal soil moisture environment. This is accomplished by conducting water directly to individual plants through laterals running along each row, instead of providing water to the entire field as with surface or sprinkler irrigation methods. In widely spaced crops, losses are reduced because only a small portion of the soil surface is susceptible to evaporation.

A wetted profile, the shape of which is largely dependent on soil characteristics, develops in the plant's root zone beneath the "trickler" or "emitter." Ideally, the area between plants and crop rows is dry and receives moisture only from incidental rainfall. Trickle irrigation saves water because only the plant's root zone is supplied with water and little water should be lost to deep percolation or soil evaporation under proper management (Figure 16). The only irrigation return flow is due to the leaching fraction necessary to prevent excessive salt buildup in the root zone. In fact, salts are often allowed to accumulate outside the wetted profile. There is no surface runoff and very little nonbeneficial consumptive use of water by weeds. Water savings are effected through the ease with which the correct amount of water is accurately applied. Trickle irrigation usually requires very skilled technical assistance for nutrient balances and fertilizer applications.

Another advantage is that trickle irrigation systems are easily automated. The multitude of lateral lines are supplied by manifold lines connected to the main line, which, in turn, connects to the water source. Generally, a control head is provided at the water source to regulate pressure and flow, and to filter suspended solids from the water. A fertilizer injection system is often incorporated into the control head (Figure 17).

For irrigation of widely spaced crops such as orchard crops, the cost of a correctly designed trickle irrigation system can be relatively low in comparison to that for solid-set or other permanent sprinkler irrigation systems. In orchards, the unit salinity control cost-effectiveness of a trickle irrigation system is comparable to that for a solid-set or permanent sprinkler system with the same level of automation. Where clogging is not a problem and emitter line maintenance is minimal, operation and maintenance costs of the trickle irrigation system are usually quite low. In plantings of row crops or vines, where the average distance between emitter lines must be less than 3 meters, the cost of trickle irrigation is relatively high.

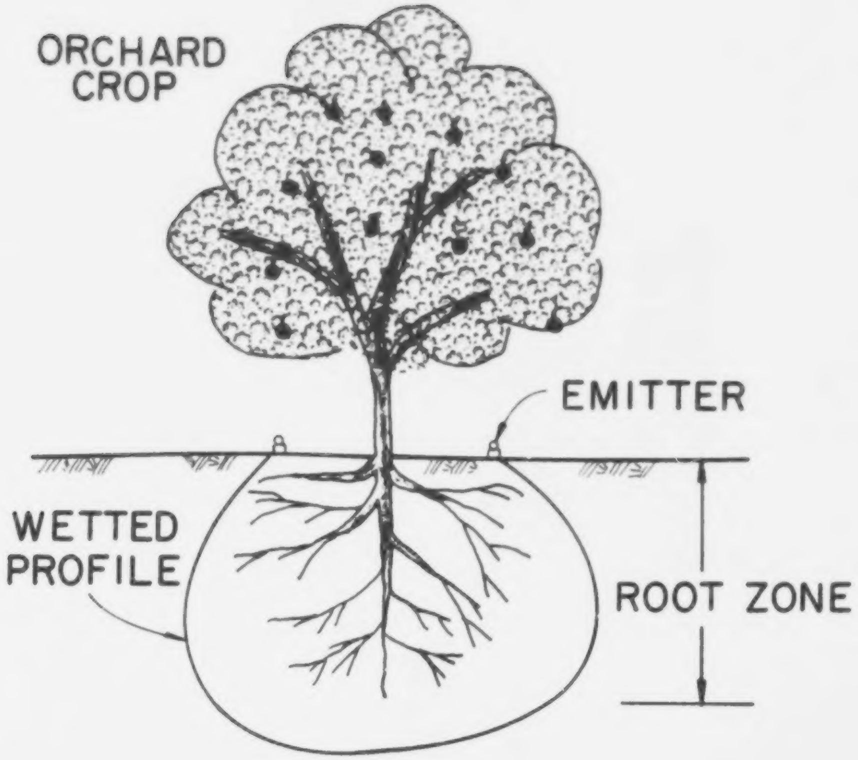

ORCHARD CROP
EMITTER
WETTED PROFILE
ROOT ZONE

Figure 16. An illustration of the concept of trickle irrigation in which only a small part of the field, the wetted profile where crop roots are growing, is irrigated by emitters bringing water to each individual plant or group of plants (Smith and Walker, 1975).

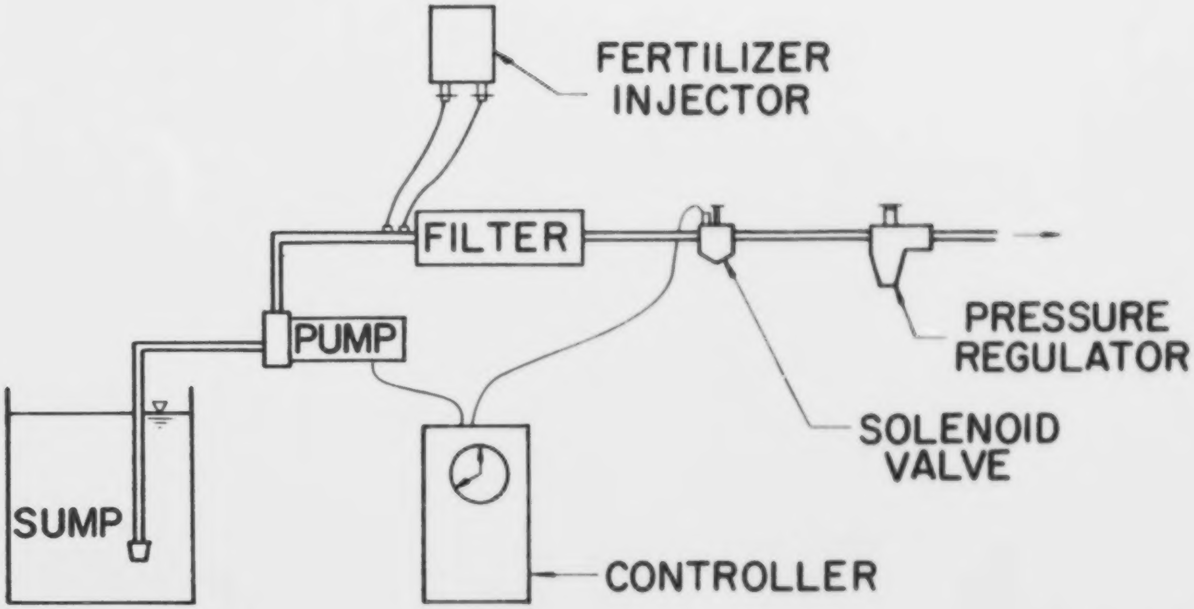

FERTILIZER INJECTOR
FILTER
PUMP
SUMP
CONTROLLER
SOLENOID VALVE
PRESSURE REGULATOR

Figure 17. A schematic diagram of a typical trickle irrigation system control head (Smith and Walker, 1975).

IMPROVING THE WATER REMOVAL SUBSYSTEM

Surface Runoff

The water removal subsystem removes the surface runoff from agricultural lands, unless it is captured and pumped back on the farm, and the deep percolation losses from irrigation. These subsystems are often very complex. For example, the surface runoff or tailwater from one farm may become all or part of the water supply for an adjacent farm. Or, the runoff may flow back into the water delivery system at some downstream location or be transported back to the river via natural or man-made open drains. Before surface return flows reach the receiving stream, there are essentially three alternatives for alleviating waterlogging and preventing or minimizing the quantity of pollutants discharged into the river. The first alternative could be a bypass channel constructed at some location where surface return flows could be discharged or treated without returning to the river.

A second alternative would be to store the return flows in shallow storage reservoirs and allow the water to evaporate, leaving behind the pollutants. Seepage must be controlled in bypass channels or storage reservoirs; otherwise, the groundwater may become contaminated. The disadvantage of the second alternative is that pollutants are collected rather than discharged to the ocean, which may eventually create another kind of disposal problem.

The third alternative for minimizing quality degradation in the receiving stream due to return flow would be to treat the return flow. Desalination processes could be used to restore the water supply to a desired quality level. Methods for disposing of brine wastes, however, must be considered.

Subsurface Drainage

Waterlogging and salinity pose a serious menace to many irrigated areas. Any expansion upslope from existing irrigated lands becomes a direct threat to the waterlogging of downslope areas. For example, many of the fertile lands in the San Joaquin Valley of California are now threatened by upslope irrigation development, and some areas in the Yuma Valley of Arizona have been rendered unproductive by irrigation development on the Yuma Mesa. Equally dangerous threats exist from the salt balance problem of these areas. Recirculation of water by pumping or the reuse of subsurface return flows results in a buildup of salinity. Concomitant with increased salinity are increases in the leaching requirement and drainage needs. Irrigation development, including impoundment, conveyance, and application, upsets the natural hydrologic cycle of an area. Recognition and the solution to drainage and salinity problems in such areas require intensive application of control measures based on sound scientific knowledge.

Tile Drainage--

If the underlying strata are sufficiently permeable, tile drainage is a very effective means of lowering the water table and facilitating movement of salts from the root zone. Two types of tile drainage are utilized in irrigated areas. The first is called field relief drainage which primarily controls the water table elevation by intercepting and removing deep percolation from the overlying root zone. Relief drainage is not able to completely remove all of the water moving below the root zone unless the water table is lowered below the natural groundwater outlet. The second type is called interception drainage in which the primary source of groundwater under a field comes from lands above. Interception drainage collects the groundwater flows at the edge of the field and conveys them downstream, thereby removing their potential to aggregate high water table conditions.

Usually, some water will still pass by the drains into the groundwater reservoir and return to the river, but the quantity of such groundwater return flows can be reduced considerably by tile drainage. The quality degradation to receiving streams by tile drainage outflow can be minimized by treating the outflow (U.S. EPA, 1971b). This stresses another advantage of tile drainage. Tile drains allow the collection of subsurface return flows into a master drainage system for ease of control and treatment. Pollution aspects of tile drainage are discussed by USDI (1972a) and the California Department of Water Resources (1971).

Pump Drainage--Pumps have been used effectively for lowering the water table in many areas. If the water is not too saline, it can be reused directly or by mixing it with the surface water supplies by discharging the flow back into laterals for irrigating croplands. The salinity of groundwater supplies varies widely, with some too saline for irrigation. For good quality groundwater supplies, pumping serves the dual purpose of alleviating waterlogging and providing additional irrigation water supplies.

In other situations, pump drainage has been used to remove highly saline groundwater in order to alleviate waterlogging and increase crop production. The primary difficulty is the disposal of these highly saline flows. Potential solutions include ponding and evaporation, conveyances and disposal in the ocean, deep well injection, or desalination as in the Wellton-Mohawk area in Arizona.

COLLECTION, TREATMENT, AND DISPOSAL OF IRRIGATION RETURN FLOWS

In many cases where salt pickup is a particularly severe problem, subsurface return flows from irrigated lands may be so brackish that no further use of the water is possible. Such flows significantly degrade the quality of a river, stream, or groundwater resource. An alternative to expenditures aimed at reducing the volume of these flows by improving irrigation efficiency is to collect the subsurface return flows before they enter receiving waters. The collected flows can then be directed to a desalination plant that removes most of the salts and returns the water to the stream or directly to a disposal area. Major disposal alternatives include deep well injection and evaporation ponds. A schematic diagram of a desalination system is shown in Figure 18. One of the applicable desalination processes for the range of salination encountered in irrigation return flows is reverse osmosis. Another process that could be applied is electrodialysis. These methods are discussed in more detail by Walker (1978a).

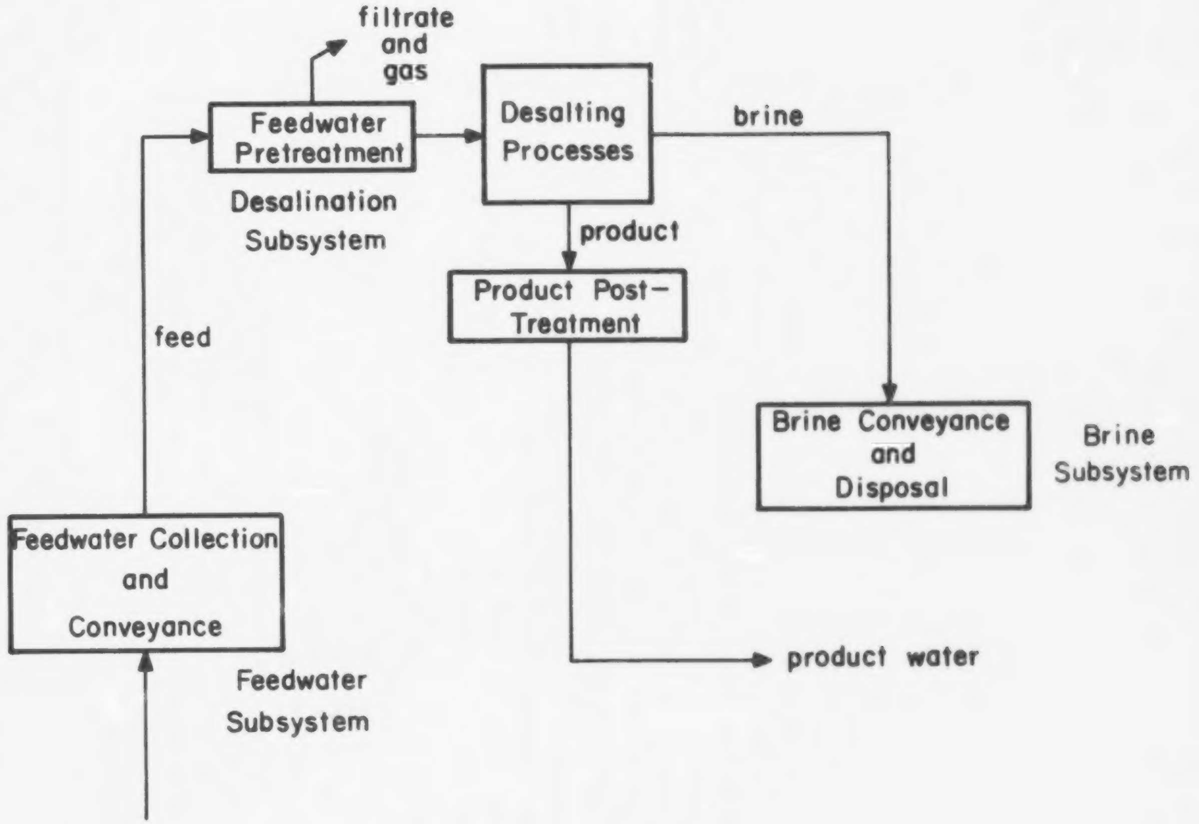

filtrate
and
gas
Feedwater Pretreatment
Desalination Subsystem
Desalting Processes
brine
product
Product Post-Treatment
feed
Brine Conveyance and Disposal
Brine Subsystem
Feedwater Collection and Conveyance
Feedwater Subsystem
product water

Figure 18. Schematic diagram of a typical desalination system (Walker, 1978a).

The costs of collection, desalination, injection wells, and evaporation ponds are described for planning purposes by the United States Department of Interior (1972b). A mathematical description of the same information is given by Walker (1978a). In general, up to a point, the costs of the collection, desalination, and brine disposal for salinity control exceeds the costs required to achieve the same level of salt reduction by improving irrigation efficiencies. However, this is not true in all cases, particularly when compared to lining large conveyance systems or implementing highly automated irrigation systems. The desalination alternative is relatively free of the institutional complications involved in improving an entire irrigated area, but is an intensive user of energy.

NONTECHNICAL ALTERNATIVES

Controlling salinity in a major river basin is a difficult task because of the mixture of diffuse and point sources of salinity. Generally, the most practicable solution lies in combining the strong features of several control measures and applying each alternative where it is best suited. Salinity control technology in this regard remains to be developed since few investigations have managed to integrate the alternatives. If the control program is to be based on "best management practices," then this integration of alternatives should be optimized in accordance with a specific criterion for selecting one measure over another. Two nonstructural alternatives which should be investigated are taxation and land retirements. Legal alternatives such as influent standards or water markets are discussed in Section 9.

Taxation

Taxation is strictly a linear application of estimated downstream damages and does not adequately incorporate the costs of treating the problem by amending local irrigation practices. Plans calling for more than this level of control could not be adequately financed by taxes alone. In other words, there is a point where the costs of alleviating salinity are greater than the downstream damages. Taxation would have to be based on a sliding scale representing the minimum cost strategy for reducing salinity. These kinds of taxes are simple repayment fees and are not generated from consideration of the entire economy.

Land Retirement

Land retirement is a viable and competitive salinity control measure in some areas such as the extensive citrus groves near Yuma, Arizona, where land retirement is being implemented. These lands do not yet have an alternative use which requires water. If these lands should develop nonagricultural water users, such as urban areas, land retirement could only be a short-term solution since urban landscapes would then be irrigated, continuing the old problem.

To determine whether land retirement can be feasible on economic efficiency grounds, two sources of information are required: (a) the direct and indirect costs of removing land from irrigation; and (b) the benefits or incremental reduction in damages that would occur as a consequence. Direct costs should accurately reflect the incomes foregone from farming of the retired irrigated lands. Included in the indirect costs should be net effects of costs and benefits issuing from resource reallocation, social transition, impacts on environmental amenities, and other consequences in the affected region.

An interindustry (input-output) model serves as the underlying structure for the analysis reported by Leathers and Young (1976). The input-output model is an analytical accounting technique commonly used in the evaluation of "total" economic impacts of exogenous (or outside-induced) changes in an economy. Because of the interdependence among industries in a well developed economy, which may include small or large regions, secondary or indirect impacts are often thought to be just as important as the primary or direct impacts of an induced change. For this reason, the basic approach adopted in the study by Leathers and Young (1976) is an indirect impact analysis.

Land retirement mechanisms might include one or more of a number of options and can be either voluntary or involuntary, depending on the level of public acceptance and participation in the program. The objective is to discontinue irrigation of selected acreages, thus eliminating all future salt loading from these sources. Specific program options evaluated by Leathers and Young (1976) involve a permanent withdrawal of water supplies.

In general, the incremental costs of salt removal for land retirement programs (in $ per metric ton), using the provisional estimates of salt loading, appear to be competitive with other more expensive controls such as canal lining, drainage, and desalting. The cost-effectiveness of the program is quite sensitive to assumptions regarding estimates of the quantity of salts removed and the value placed on the salts removed. Accordingly, it is important that these assumptions be considered very carefully in comparing alternative salinity control programs.

The future uses of the land which would be retired is also an important consideration. For example, in the Grand Valley, there is substantial urbanization occurring and lands retired would sell for high prices to be developed as housing sites. Many areas in the Valley already converted to subdivisions utilize the water previously diverted for agriculture. Every local indication implies the urban irrigator requires more water to irrigate a smaller vegetative area. This is due to lower water use efficiencies resulting from existing horticultural practices for landscape maintenance in the areas. It does not appear that land retirement would be a long-term solution to the salinity problem in that area.

SECTION 5

INFLOW-OUTFLOW ANALYSIS

Irrigated agriculture is generally a small part of the hydrologic system in major watersheds as illustrated in Figure 19. The first step in evaluating salinity resulting from irrigated sources is to delineate the irrigated segment from the hydrology. This is usually accomplished with an inflow-outflow analysis which is the first level of modeling for irrigated agriculture.

Inflow-outflow analysis is used to determine if there is a significant salinity problem. It is conducted on a macroscale and shows aggregate pollution as a result of activities in an area without identifying individual sources or which control measures would be appropriate. The application of input-output analysis on intervals of less than one year is difficult to accurately accomplish since internal storage changes within the system are difficult to quantify in smaller time increments. Because inflow-outflow analysis is relatively simple, computer programs are not generally required for these calculations.

Due to the simplicity of inflow-outflow analysis, these procedures are very useful to 208 planning efforts. Inflow-outflow computations can indicate the priority and the types of initial investigations that should be conducted on local areas, subdrainage areas, or river basins. These analyses are usually done with existing data and, therefore, they can be expeditiously completed.

PROCEDURE

Assessment of inflows and outflows in a region determines the salinity loads above and below the irrigated areas. Differences in salinity loads represent the total salt load discharged by the area, including background and point sources, as well as irrigation return flows. Salt loadings from irrigation are determined by subtracting the contributions from background and known point sources from the total difference of salinity loads above and below the irrigated areas.

The types of data usually needed for this analysis are river inflows to the area, tributary inflows, subsurface inflows, surface outflows, subsurface outflows, reservoir operations, and the associated water quality parameters of each of the above. The basic equation, referring to Figure 19, and not considering natural precipitation in the area is:

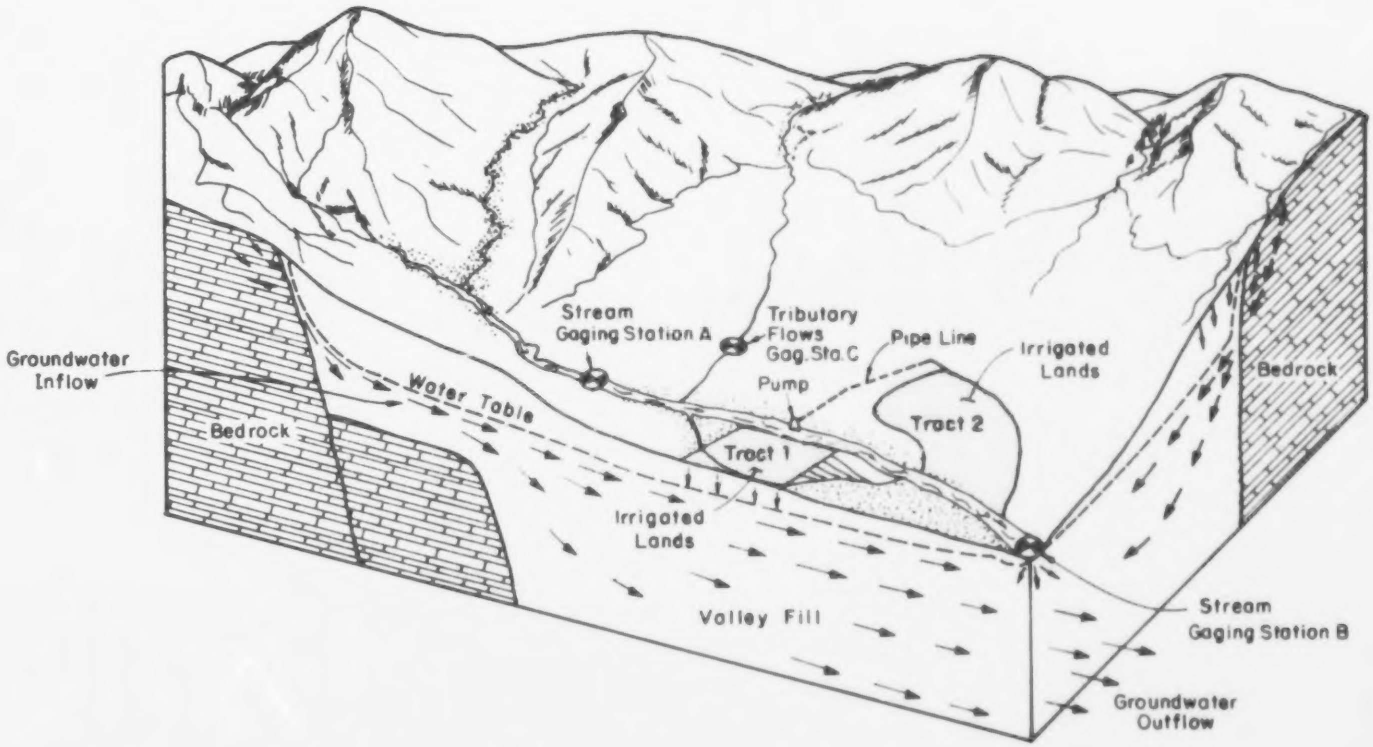

Stream
Gaging Station A
Tributary
Flows
Gag. Sta. C
Pipe Line
Irrigated
Lands
Groundwater
Inflow
Water Table
Pump
Tract 2
Bedrock
Bedrock
Tract 1
Irrigated
Lands
Valley Fill
Stream
Gaging Station B
Groundwater
Outflow

Figure 19. An illustration of a watershed which includes an irrigated component.

$$S_{IRF} = a\left(Q_{RB}\, C_{RB} - Q_{TC}\, C_{TC} - Q_{RA}\, C_{RA}\right) - S_{BG} - S_{PT} \tag{1}$$

where S_{IRF} = salinity load in irrigation return flows

Q_{RB} = streamflow (and groundwater outflow, if known) below the irrigated area from gaging Station B

Q_{RA} = streamflow (and groundwater inflow, if known) above the irrigated area from gaging Station A

Q_{TC} = combined (net) streamflow of any tributary streamflows into the irrigated area between the points of measurement, including all exports and imports of water from gaging Station C

C_{RB} = the concentrations of total dissolved solids (TDS) in the stream below, above and from the tributaries, respectively,

C_{RA} in parts per million (ppm) or milligrams per liter (mg/ℓ)

C_{TC} (mg/ℓ)

S_{BG} = salinity contribution of the background (naturally occurring salinity in the area, if it is known)

S_{PT} = salinity contribution of point sources in the area

a = conversion constant that depends upon the units used in the other variables (if Q is in acre-feet), a = 0.00036, S is in English tons; if Q is liters/sec, a = 0.0864, S is in Kg/day; if Q is in cfs, a is 5.39, S is in lbs/day)

Equation 1 is a form of the basic mass balance hydrologic equation,

$$Q_A - Q_B = \Delta S \tag{2}$$

where Q_A is the inflow, Q_B is the outflow and ΔS is the change in storage within the confines of the gaging stations. For purposes of discussing simplified areas, two irrigated tracts are shown in Figure 20. The inflow-outflow analysis is represented by the difference in the two stream gaging stations, A and B. Tributary and groundwater fluxes over the system boundaries are neglected for this case.

The inflow-outflow analysis between stream gaging stations A and B does not yield any information regarding the differences between the two tracts. Installation of an additional stream gaging station on the river between the two tracts would enable analysis of the inflow-outflow of only one tract of irrigated land. However, this depends upon the geology and its effects upon subsurface return flows.

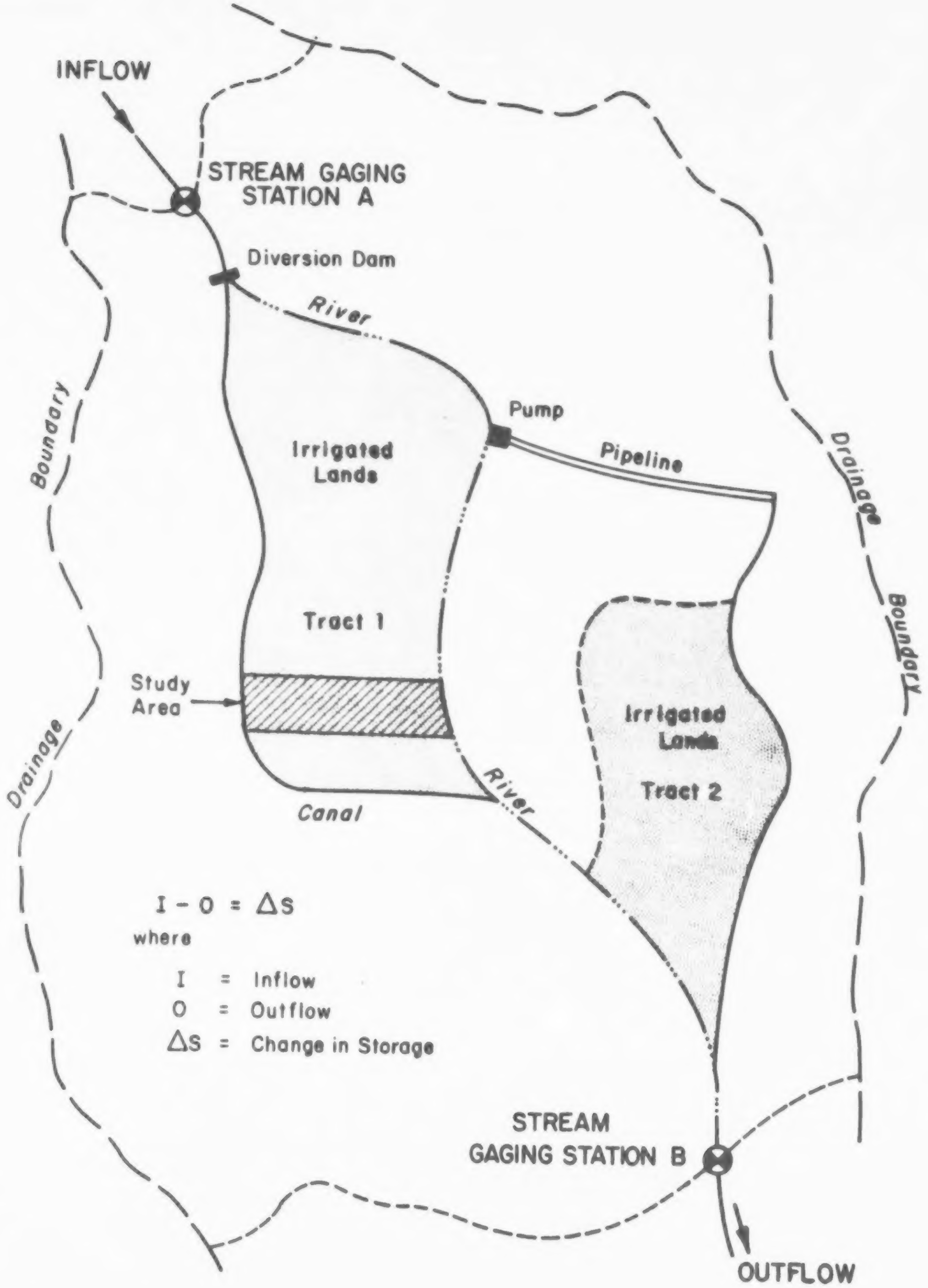

INFLOW
STREAM GAGING STATION A
Diversion Dam
River
Pump
Pipeline
Irrigated Lands
Tract 1
Study Area
Boundary
Drainage
Drainage
Boundary
Canal
River
Irrigated Lands
Tract 2
I - O = ΔS
where
I = Inflow
O = Outflow
ΔS = Change in Storage
STREAM GAGING STATION B
OUTFLOW

Figure 20. Schematic example of inflow-outflow analysis.

The flow of salts into and out of the area can thereby be represented by:

$$Q_A C_A - Q_B C_B = \Delta S_s \qquad (3)$$

in which C_A and C_B are the salinity concentrations at the respective gaging stations and ΔS_s equals the change in salt storage within the systems. If ΔS_s is considered as the solution phase, mass balance for the salts may not be achieved with Equation 3 because of the salt pickup or precipitation phenomenon. If ΔS_s is positive, salts are accumulating in the soil profile of the irrigated lands, whereas if $\Delta S_s = 0$, a salt balance is maintained.

If ΔS_s is negative and salt pickup is occurring, it is difficult to determine the source of the pickup. This also indicates the shallow groundwater flows would be highly saline. Providing data is available, a long-term history of salt pickup will disclose whether the pickup rate is increasing, remaining fairly constant, or declining. A declining salt pickup rate indicates that natural salts in the soil profile from either irrigated or watershed areas are being dissolved and transported into the groundwater reservoir enroute to the river. A relatively constant salt pickup rate indicates a large source of salts in comparison with the amount of water percolating through the soil profile and moving through the groundwater reservoir. Additional analysis, such as hydro-salinity analysis, is required to determine the magnitudes of the salt pickup resulting from irrigated agriculture and natural runoff. Also, saline water from mineralized springs could significantly contribute to the accumulation of salts. An increasing salt pickup rate indicates the existence of man-made activities, such as increasing irrigated acreages, or poorer water management on existing irrigated lands.

DATA COLLECTION

These types of analyses are usually done with existing data, and there is little need for field data collection unless there are no stream gaging stations above or below the irrigated area, or sufficient salinity concentration data have not been collected. For this reason, the input-output analysis is often done only with surface water records since they are usually readily available, although groundwater inflows and outflows should be included if they can be quantified.

Flow and chemical concentration data can be obtained from several sources. The most common sources are the annual United States Geological Survey summaries of water flow and quality data for each state. The United States Geological Survey also publishes a catalog on available water data (United States Geological Survey, 1975). This type of data is often gathered by other Federal agencies such as the United States Army Corps of Engineers, the United States Department of the Interior (Bureau of Land Management and Bureau of Reclamation), the United States Department of Agriculture (Soil Conservation Service, Science and Education Administration, Forest Service) and the United States Environmental Protection Agency. Other sources for flow data are the state agencies such as the State Engineers Office, natural resource groups, state health and environmental protection agencies, and universities and colleges conducting research in the area.

Local organizations such as the local health departments, environmentalist groups, fisheries and wildlife personnel, consulting engineers or industries, power plants and mining operations also collect data in conjunction with EPA discharge permit requirements or other programs. Sometimes the data are collected for purposes other than salinity, but can often be utilized in these studies.

Climatic data are published by the National Weather Service, as well as some state and local research and extension agencies. Land use data are collected annually by the United States Department of Agriculture, Agricultural Stabilization Conservation Service. The periodic Census of Agriculture can also provide valuable information.

Since most of these data are general, care must be taken to understand their limitations and the resulting degree of accuracy that can be expected in the analysis. The *frequency* of sampling is very important and the *validity* of the sampling techniques should also be considered. Many of the United States Geological Survey gaging stations have ratings that serve as a guide to their estimated accuracy.

The type of data collected is also important. For example, mineral concentrations are usually given in terms of electrical conductance (EC) and temperature. Laboratory analysis is required to establish the relationship between EC and the total dissolved solids (TDS), as well as the ionic composition of the water. For most surface waters of fairly good quality (TDS $<$ 1000 ppm), a ratio of EC to TDS is usually about 0.65 when EC is in units of micromhos/cm (μmhos/cm). For saline groundwater or leachate, this ratio varies considerably between 0.65 and unity. The United States Salinity Laboratory uses $TDS \approx EC \times 928$ where EC is in millimhos/cm (mmhos) for this case. The relationship is not linear and depends upon the chemical properties of the water, particularly on the concentrations of sulfates. Hem (1970) presents more information on the interpretation and analysis of the chemical characteristics of natural waters.

In the western United States, streamflow records are usually very good and readily available; however, water quality data are often lacking and must be estimated or computed. In addition, the length of time records were kept for water quality data may be very short. The Water Resources Council (1966) has provided a review of techniques and limitations of various hydrologic data analyses. For quick and very rough estimation purposes, publications such as Geraghty et al. (1973), Rainwater (1962), or Todd (1970) can be helpful.

Computational Methods

The type of computational methods utilized depends upon the kind, variability, and frequency of the data to be used. If much data are missing and must be estimated, there are many statistical and stochastic methods available (Yevjevich, 1972, and Riggs, 1968). The usual procedure is to generate daily streamflows with corresponding dissolved mineral concentrations. If that is not possible, a discharge weighted average analysis is sometimes appropriate. This method uses composite sampling in an attempt to minimize errors and variance and to approximate the composition of all the water which passed the station that year. This method is usually used in combination with good streamflow records and sporadic water quality records.

Another method for computing salt loads, which is essentially the same as above except for the time scale, is to multiply the daily TDS by the daily streamflows, then sum the values to get the yearly total of salt that passed the station. This is a good technique when very good streamflow and chemical quality data exist.

If only infrequent data are available, the use of linear or nonlinear regression equations are often used to predict mineral quality parameters. The most common regressions are of discharge versus EC, and EC versus TDS in conjunction with daily flows. The daily values are summed to give the annual salt loading. This method has been used by the United States Geological Survey with fair success in the Upper Colorado River Basin (Brennan and Grozier, 1976) and in other areas.

SECTION 6

HYDRO-SALINITY ANALYSES

The evaluation of the hydrologic and salinity parameters for an area requires a large amount of data and lengthy computational procedures. Hydro-salinity modeling is necessary to determine the magnitude and effect of each segment of the hydrologic system. A water and salt budgeting procedure is typically used that is essentially a mass balance or conservation of mass approach. Numerous computer models have been formulated for water and salt budgeting. Walker (1978b) reviewed 43 of these models, some of which are described in Appendix A.

The hydro-salinity procedure integrates various aspects of the local hydrology. For example, measured flows diverted from the river into the main conveyance system are segregated into measured seepage and measured lateral diversions. Operational losses are calculated by the difference between the main diversion, seepage and lateral diversions. The lateral diversions are likewise delineated into seepage and root-zone diversions (measured). Root-zone diversions are further separated into root-zone soil moisture storage (measured and/or computed), deep percolation (usually by difference, but sometimes measured) and consumptive use (measured or computed).

Evaluation of the salinity sources is conducted on several levels with objective procedures that systematically and continuously refine the various elements of the hydro-salinity flows to the required degree of accuracy. There are basically four steps for this evaluation procedure:

1. Definition of the components of the hydrologic system as to their function, such as water delivery, water use, or water removal.

2. Establishment of a large-scale instrumentation network to monitor the quantity and quality of each component of the hydrologic system for the area.

3. Establishment of criteria for classifying the existing performance of the various subsystems for both time-specific events and seasonal or annual analysis.

4. Definition of the relationships expressing the existing system performance as functions of management and/or methods of operation.

Defining the components of the hydrologic system is necessary in order to properly design a monitoring network that evaluates pollution effects and contributions from each subsystem. The next step is to establish the network of instrumentation to monitor the surface and groundwater hydrology and to define the hydrologic components of the area in question. A monitoring network usually consists of flow measurement structures that collect information on canal, headgate, on-farm diversions, and surface tailwater flows. A network of observation wells and piezometers is required to collect information on groundwater gradients, flows, and elevations for subsurface returns to the rivers or lakes. Water quality information is also collected from all of these sources simultaneously with the other measurements. A generalized monitoring network for hydro-salinity investigations is presented in Figure 21. From an anlysis of these data, the total on-farm component of the irrigation hydrology is determined. A smaller study area of several farms should then be selected for farm efficiency investigations, and the individual segments of this subsystem evaluated. An implementation program can then be initiated on this study area and any changes in conditions caused by the small-scale implementation program should be reflected in the larger monitoring network.

DEVELOPING WATER BUDGETS

The process of hydro-salinity modeling is basically one of formulating a series of water budgets for each hydrologic segment. These budgets are expansions of the mass balance hydrologic equation presented in the previous section. This is the first step of hydro-salinity investigations.

The most important consideration for developing water balances is to select the system boundaries to use the available information to the best advantage. This boundary selection procedure will also assist in designing the monitoring network and in determining the extent of the field investigations. Many of the variables such as canal diversions are known, but it is necessary to develop as many water balance equations as there are unknown variables. The time frame, monthly or yearly, of the budgets must be determined at the start of the process.

Establish Water Budget Equations

The following example is developed for purposes of illustration of the procedures and consideration involved in the hydro-salinity process. In specific cases, there may be more or less variables than are presented in this example; and many variables may be insignificant or zero. In this simplified case, four equations were developed for the selected hydrologic subsystems. These equations are:

1. Water Balance on a Channel

   One segment of the hydrologic system is just the physical boundaries of the river channel, and a water balance equation can be written for this subsystem. For example:

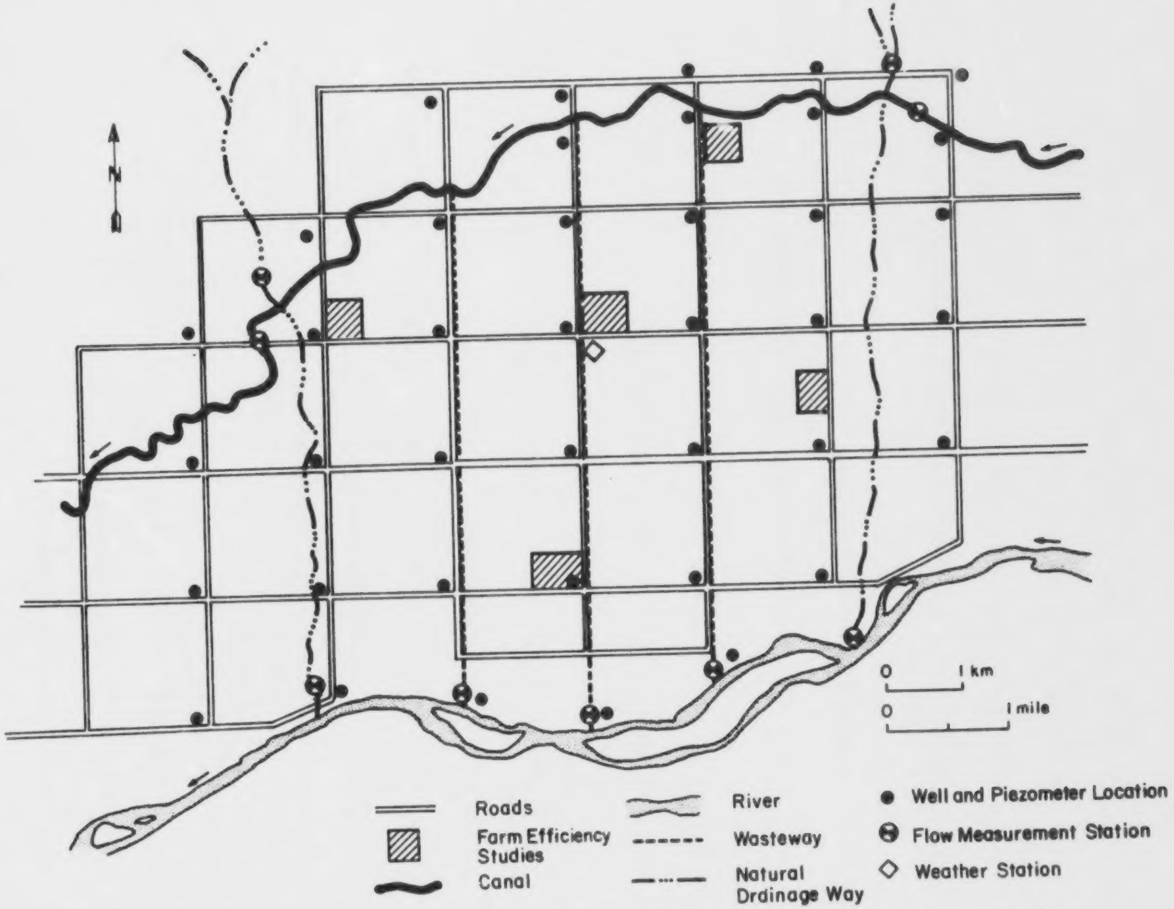

N
0 1 km
0 1 mile
Roads
Farm Efficiency Studies
Canal
River
Wasteway
Natural Drdinage Way
Well and Piezometer Location
Flow Measurement Station
Weather Station

Figure 21. Delineation of a study area and a possible monitoring network for a hydrosalinity investigation.

$$Q_A+Q_{SRF}+Q_{IRF}+Q_{RP}+Q_{RR}+Q_R+Q_{CS}-Q_{ID}-Q_{SD}-Q_{RE}-Q_B-\Delta S_{RS}=0 \tag{4}$$

where Q_A = river inflows at point A

Q_B = river outflows at point B

Q_{SRF} = seepage returns from surface storage

Q_{IRF} = subsurface irrigation return flows including ditch seepage

Q_{RP} = precipitation on river

Q_{RR} = natural surface runoff from precipitation to river

Q_R = surface runoff from irrigation

Q_{CS} = canal spillage returns to river

Q_{ID} = irrigation diversions

Q_{SD} = diversions for reservoir storage

Q_{RE} = river evaporation

ΔS_{RS} = change in storage in river channel

2. Water Balance on Surface Storage

If an area has surface reservoir storage facilities, a water balance can be written for this hydrologic subsystem.

$$Q_{SD}+Q_{SP}-Q_{SE}-Q_{SR}-Q_{SRF}-\Delta S_{SS}=0 \tag{5}$$

where Q_{SD} = diversions for reservoir storage

Q_{SP} = precipitation on storage

Q_{SE} = surface evaporation

Q_{SR} = reservoir releases to irrigation

Q_{SRF} = seepage returns to river from storage

ΔS_{SS} = change in surface storage

3. Water Balance on Soil Surface and Root-Zone

One hydrologic subsystem which can be defined is the soil surface and the root-zone as a unit. Neglecting bank storage, the mass balance equation which can be written for this system is:

$$Q_P+Q_{ID}+Q_{SR}+Q_{PW}-Q_{ET}-Q_{DP}-Q_R-\Delta S_{SM}=0 \tag{6}$$

where Q_P = precipitation on croplands

Q_{ID} = irrigation diversion

Q_{SR} = reservoir releases to irrigation

Q_{PW} = pumped water

Q_{ET} = evapotranspiration

Q_{DP} = deep percolation

Q_R = surface runoff

ΔS_{SM} = change in soil-moisture storage

4. Water Balance on Aquifer

In writing the mass balance for this hydrologic subsystem, it was assumed that groundwater inflows and outflows at point A and B are equal, and that there is an impermeable substrata. The equation is therefore:

$$Q_{DP}+Q_{SRF}-Q_{PET}-Q_{PW}-Q_{BSG}-Q_{IRF}-\Delta S_A=0 \tag{7}$$

where Q_{DP} = deep percolation

Q_{SRF} = seepage from reservoirs

Q_{PET} = phreatophyte evapotranspiration

Q_{PW} = pumped water

Q_{BSG} = contributions from bank storage and groundwater

Q_{IRF} = subsurface irrigation return flows to river

ΔS_A = change in aquifer storage

In some cases, this equation can be simplified by assuming that Q_{SRF} is not transient and equals Q_{BSG} over a one-year period and cancels. Due to the manner in which the boundaries of hydrologic subsystems were initially selected, it is possible to further reduce the number of variables by adding the mass balance equations of 6 and 7 above. In which case the resulting equation is:

$$Q_{ID}+Q_{SR}+Q_{P}-Q_{ET}-Q_{PET}-Q_{R}-Q_{IRF}-\Delta S_{SM}-\Delta S_{A}=0 \qquad (8)$$

where the Q_{PW} has been eliminated. With justification, additional assumptions can be made to simplify the equation, such as setting $Q_R=0$ and $\Delta S_{SM} \simeq 0$ over a month. Q_{ET} can be divided into $Q_{ETP}+Q_{ET_I}$ where Q_{ETP} is the evapotranspiration from precipitated water and Q_{ET_I} is the evapotranspiration from irrigation diversions. If it is assumed that precipitation is 100 percent effective, then Q_P can be equal to Q_{ETP}. The equation now can be written as:

$$Q_{ID}+Q_{SR}-Q_{ET_I}-Q_{PET}-Q_{IRF}-\Delta S_{a}=0 \qquad (9)$$

For purposes of salinity control, the most important term in this equation is Q_{IRF}, and the others can be calculated or measured through the information collected by the monitoring network. The subsurface irrigation return flows can be calculated analytically by methods proposed by Glover (1975) and others, or by use of a suitable numeric hydro-salinity computer model. The results are then applied back through the other water balance equations until all the unknowns are determined. From the simplified water budgeting (water balancing) example presented above, it can be seen that the proper selection of the hydrologic subsystem boundaries can greatly simplify the calculations and the analysis.

DELIVERY SUBSYSTEM

The delivery subsystem consists of canals and laterals. Each segment contains three surface water components that must be identified. These are (a) diversions, (b) internal water accretions, and (c) operational losses that include spillage and flow measurement errors.

The first step is collection of time distributed records on canal diversions from the river or reservoir. These records are usually available from state or federal agencies and the irrigation companies. The irrigation companies can usually supply time distributed headgate diversion records, and sometimes have on-farm diversion records as well. However, in most cases, the farm diversions must be collected by project personnel.

Usually, the internal accretions to a delivery subsystem are not measured by any of the aforementioned agencies, but must be collected to do proper mass balance analyses. These additional sources of water can come from drainage wells or supplemental irrigation wells, return flows from higher lands, groundwater inflows, if the canal passes through a high water table area, and intermittent streams, washes and drains that intersect the canal system.

Operational losses, often called administrative losses, primarily consist of spillage, but also include all measurement errors that cannot be accounted for by other means. Spillage is water returned to the river as a result of canal or lateral discharges for the purpose of regulating water levels in the delivery subsystem. In many areas, total spillage is about 5 to 10 percent of the total diversions, while in extreme cases it can be as high as 30 to 50 percent.

Surface hydrology of an area is usually easy to define. Flows can be measured by standardized methods with minimal error. However, to adequately account for all surface flows in a large area may require extensive instrumentation and/or personnel to collect and analyze data. It is primarily for this reason, and due to the nature of concurrent subsurface investigations, that a small area is usually heavily instrumented and the results extended to the larger area.

Seepage from canals, laterals and other channels must be determined. For example, the effectiveness of existing linings, proposed lining, or conversion to closed conduits for canals and laterals cannot be assessed without proper seepage measurements. Seepage measurements are also normally used to define conveyance efficiency functions that are used for calculations in the hydro-salinity model. Seepage measurement techniques are discussed in Section 8.

FARM SUBSYSTEM

Evaluation of existing on-farm water application methods is one of the most important parts of any hydro-salinity investigation. The irrigation and cultural practices of a grower affect many of the parameters of irrigation return flows. For example, cultural practices can influence the infiltration and erosion properties of the soil. The irrigation practices, including the type of irrigation system, time duration of individual sets, and field size affect the application efficiency, the uniformity of water application over the entire field, volume of surface runoff, soil moisture storage, and deep percolation.

Evaluation of on-farm water application practices must be done with respect to the individual irrigation event and the seasonal or annual irrigation practices. Each irrigation of the season needs to be individually evaluated to determine the seasonal impact of irrigation for that field. These evaluations must be reduced into the subcategories of irrigation management and the irrigation method considerations. These relationships are quantified in terms of the irrigation performance. This procedure and interrelationships of the on-farm subsystem are illustrated in Figure 22.

Irrigation performance, as used in this manual, is defined as the aggregate result of the water application characteristics of the individual irrigation system and the quality of irrigation management provided by the grower. The evaluation of irrigation performance at each of the two levels should define the performance in relation to irrigation management practices and physical operational capabilities or conditions of that system. These relationships identify the specific effects and results of irrigation on the soil and the area.

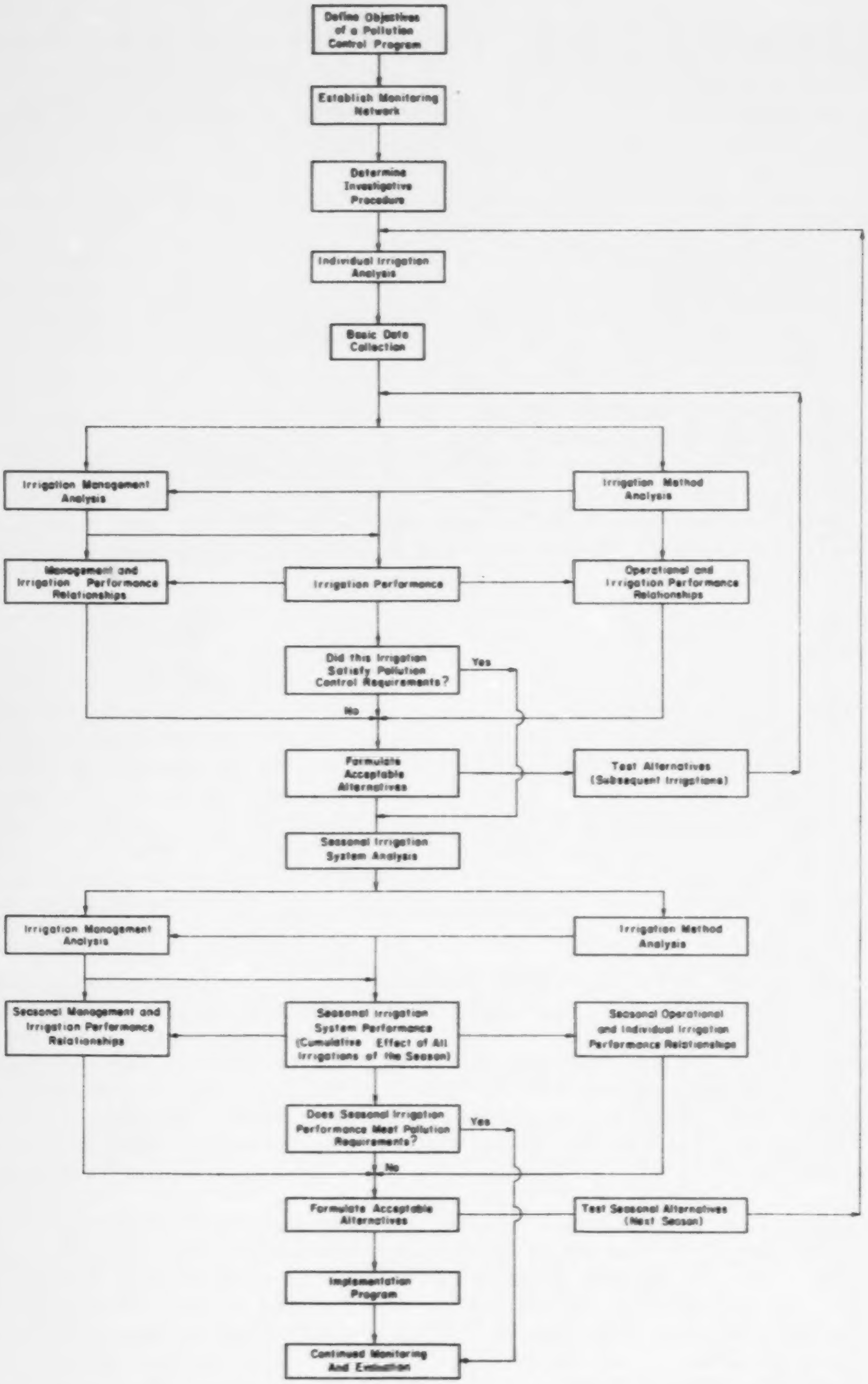

Define Objectives of a Pollution Control Program
Establish Monitoring Network
Determine Investigative Procedure
Individual Irrigation Analysis
Basic Data Collection
Irrigation Management Analysis
Irrigation Method Analysis
Management and Irrigation Performance Relationships
Irrigation Performance
Operational and Irrigation Performance Relationships
Did this Irrigation Satisfy Pollution Control Requirements?
Yes
No
Formulate Acceptable Alternatives
Test Alternatives (Subsequent Irrigations)
Seasonal Irrigation System Analysis
Irrigation Management Analysis
Irrigation Method Analysis
Seasonal Management and Irrigation Performance Relationships
Seasonal Irrigation System Performance (Cumulative Effect of All Irrigations of the Season)
Seasonal Operational and Individual Irrigation Performance Relationships
Does Seasonal Irrigation Performance Meet Pollution Requirements?
Yes
No
Formulate Acceptable Alternatives
Test Seasonal Alternatives (Next Season)
Implementation Program
Continued Monitoring And Evaluation

Figure 22. Schematic representation of the investigative procedure for evaluation of specific irrigation events and seasonal irrigations.

When the irrigation performance has been established, it is then necessary to evaluate the system in terms of pollution control objectives. If the system does not meet these requirements, the parameters or other potential management and/or operation conditions that cause the system to conform must be defined, and acceptable alternatives for their implementation must be formulated. These alternatives should then be tested on subsequent irrigations or seasons using the same procedures as outlined above. The results are utilized to provide direction for a full-scale implementation program.

An evaluation of each irrigation event throughout the irrigation season is necessary because several environmental factors can change with time. For example, infiltration functions generally decrease as the irrigation season progresses because of soil compaction and soil sealing effects of sediment and chemical action. In addition, salinity and ionic balances change due to concentrating effects and nutrient movements and off-season leaching. The elevations and the respective chemical composition and concentrations of the groundwater vary significantly throughout the year. A detailed schematic of the factors to consider in the individual irrigation analysis is presented in Figure 23, and for the seasonal analysis in Figure 24.

When evaluating an irrigation system, the fields and crops should be representative of conditions encountered in the entire area, and all tests should be run at a time corresponding to when the crop is to be irrigated. Or, if the land is not irrigated at all, tests such as infiltration determinations should be conducted at a time when the soil moisture is relatively low. Extra effort should be made to ensure that conditions of the tests closely approximate the actual conditions of irrigation. For example, infiltration tests should use the same water which is used for irrigation.

The evaluation of on-farm irrigation systems for salinity control is primarily concerned with developing alternatives for the control of the volume of deep percolation. Figure 25 illustrates many of the parameters that must be considered in the formulation of these alternatives. The collection of these data is discussed in Section 8.

WATER REMOVAL SUBSYSTEM

The surface hydrology aspect of the water removal subsystem is concerned with conveyance channels that return excess water (tailwater) from the ends of the fields to wastewater channels that carry all other sources of excess water, including canal and lateral spillage, to the river. These wastewater channels often function as open drains and carry some intercepted groundwater flows. Since this is a conveyance system similar to the delivery subsystem, there are flow quantities, internal accretions, and outflows that must be measured or indirectly determined. The surface hydrology component of the water removal subsystem has basically the same criteria as the surface hydrology component of water delivery subsystem. Therefore, data requirements and evaluation methodology are similar.

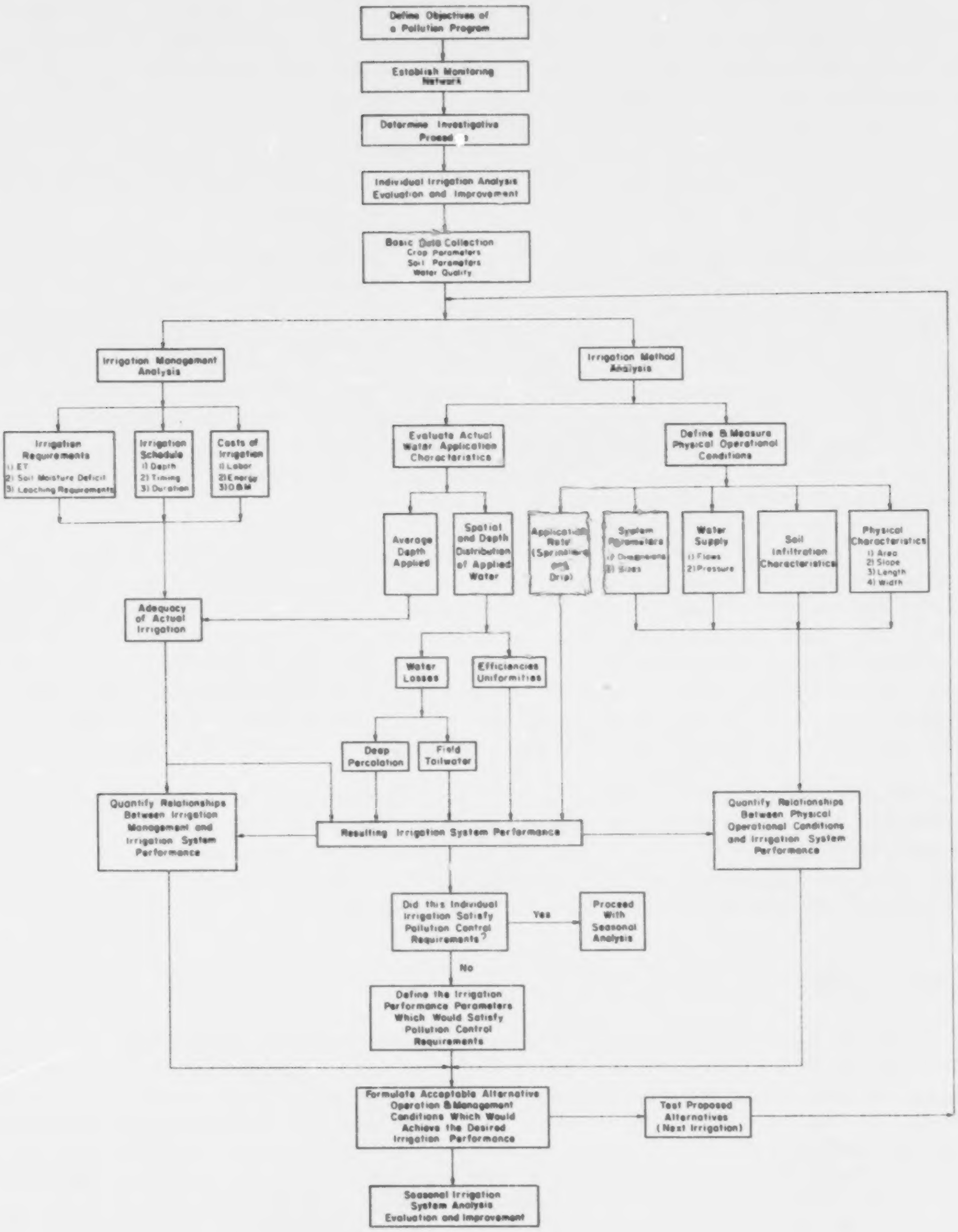

Define Objectives of a Pollution Program
Establish Monitoring Network
Determine Investigative Procedures
Individual Irrigation Analysis Evaluation and Improvement
Basic Data Collection
Crop Parameters
Soil Parameters
Water Quality
Irrigation Management Analysis
Irrigation Method Analysis
Irrigation Requirements
1) ET
2) Soil Moisture Deficit
3) Leaching Requirements
Irrigation Schedule
1) Depth
2) Timing
3) Duration
Costs of Irrigation
1) Labor
2) Energy
3) O & M
Evaluate Actual Water Application Characteristics
Define & Measure Physical Operational Conditions
Average Depth Applied
Spatial and Depth Distribution of Applied Water
Application Rate (Sprinklers and Drip)
System Parameters
1) Dimensions
2) Sizes
Water Supply
1) Flows
2) Pressure
Soil Infiltration Characteristics
Physical Characteristics
1) Area
2) Slope
3) Length
4) Width
Adequacy of Actual Irrigation
Water Losses
Efficiencies Uniformities
Deep Percolation
Field Tailwater
Quantify Relationships Between Irrigation Management and Irrigation System Performance
Resulting Irrigation System Performance
Quantify Relationships Between Physical Operational Conditions and Irrigation System Performance
Did this Individual Irrigation Satisfy Pollution Control Requirements?
Yes
Proceed With Seasonal Analysis
No
Define the Irrigation Performance Parameters Which Would Satisfy Pollution Control Requirements
Formulate Acceptable Alternative Operation & Management Conditions Which Would Achieve the Desired Irrigation Performance
Test Proposed Alternatives (Next Irrigation)
Seasonal Irrigation System Analysis Evaluation and Improvement

Figure 23. Detailed schematic for individual irrigation event on-farm subsystem analyses.

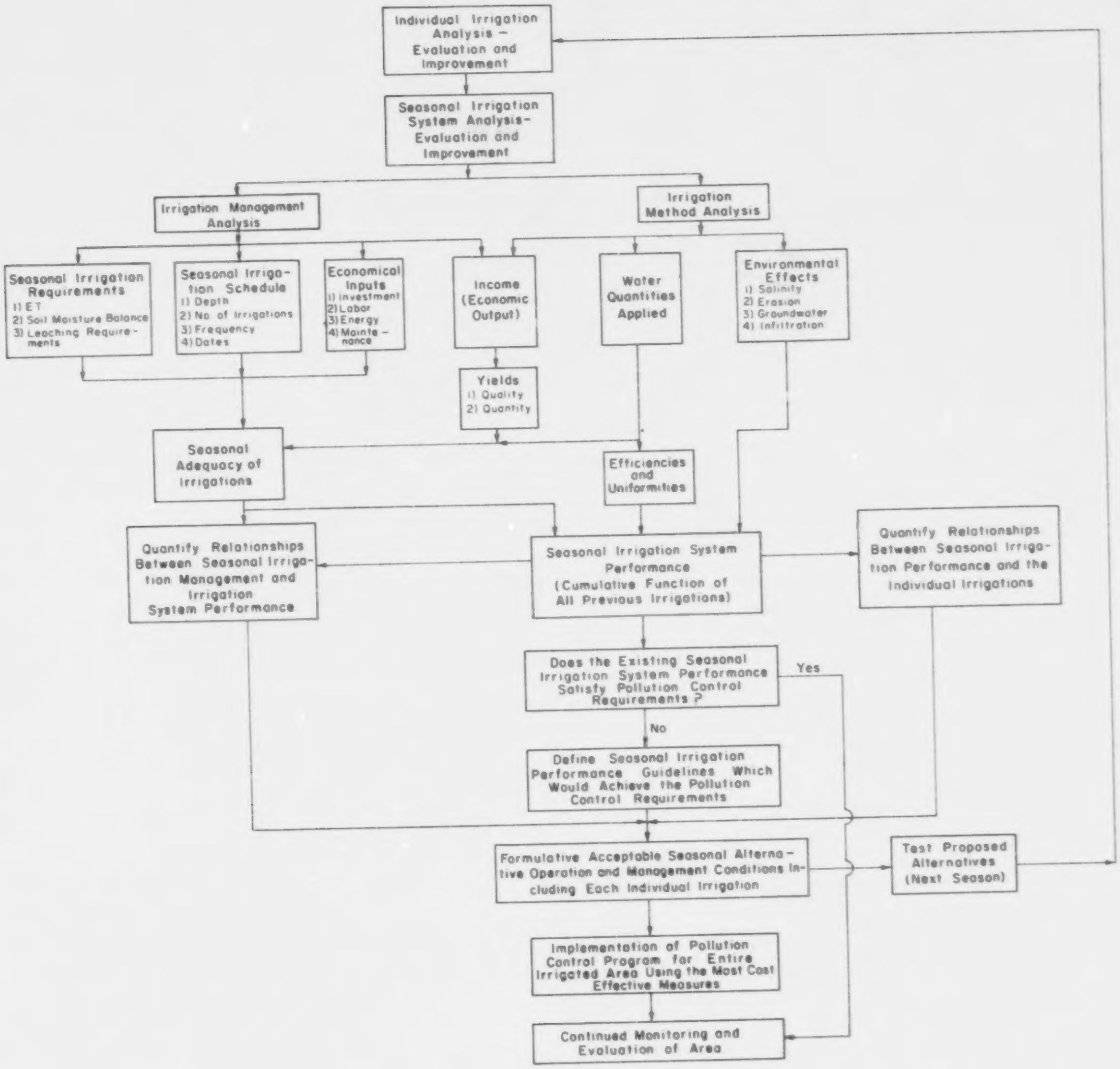

Individual Irrigation Analysis – Evaluation and Improvement
Seasonal Irrigation System Analysis– Evaluation and Improvement
Irrigation Management Analysis
Irrigation Method Analysis
Seasonal Irrigation Requirements
1) ET
2) Soil Moisture Balance
3) Leaching Requirements
Seasonal Irrigation Schedule
1) Depth
2) No. of Irrigations
3) Frequency
4) Dates
Economical Inputs
1) Investment
2) Labor
3) Energy
4) Maintenance
Income (Economic Output)
Water Quantities Applied
Environmental Effects
1) Salinity
2) Erosion
3) Groundwater
4) Infiltration
Yields
1) Quality
2) Quantity
Seasonal Adequacy of Irrigations
Efficiencies and Uniformities
Quantify Relationships Between Seasonal Irrigation Management and Irrigation System Performance
Seasonal Irrigation System Performance (Cumulative Function of All Previous Irrigations)
Quantify Relationships Between Seasonal Irrigation Performance and the Individual Irrigations
Does the Existing Seasonal Irrigation System Performance Satisfy Pollution Control Requirements ?
Yes
No
Define Seasonal Irrigation Performance Guidelines Which Would Achieve the Pollution Control Requirements
Formulative Acceptable Seasonal Alternative Operation and Management Conditions Including Each Individual Irrigation
Test Proposed Alternatives (Next Season)
Implementation of Pollution Control Program for Entire Irrigated Area Using the Most Cost Effective Measures
Continued Monitoring and Evaluation of Area

Figure 24. Detailed schematic for seasonal on-farm subsystem analyses.

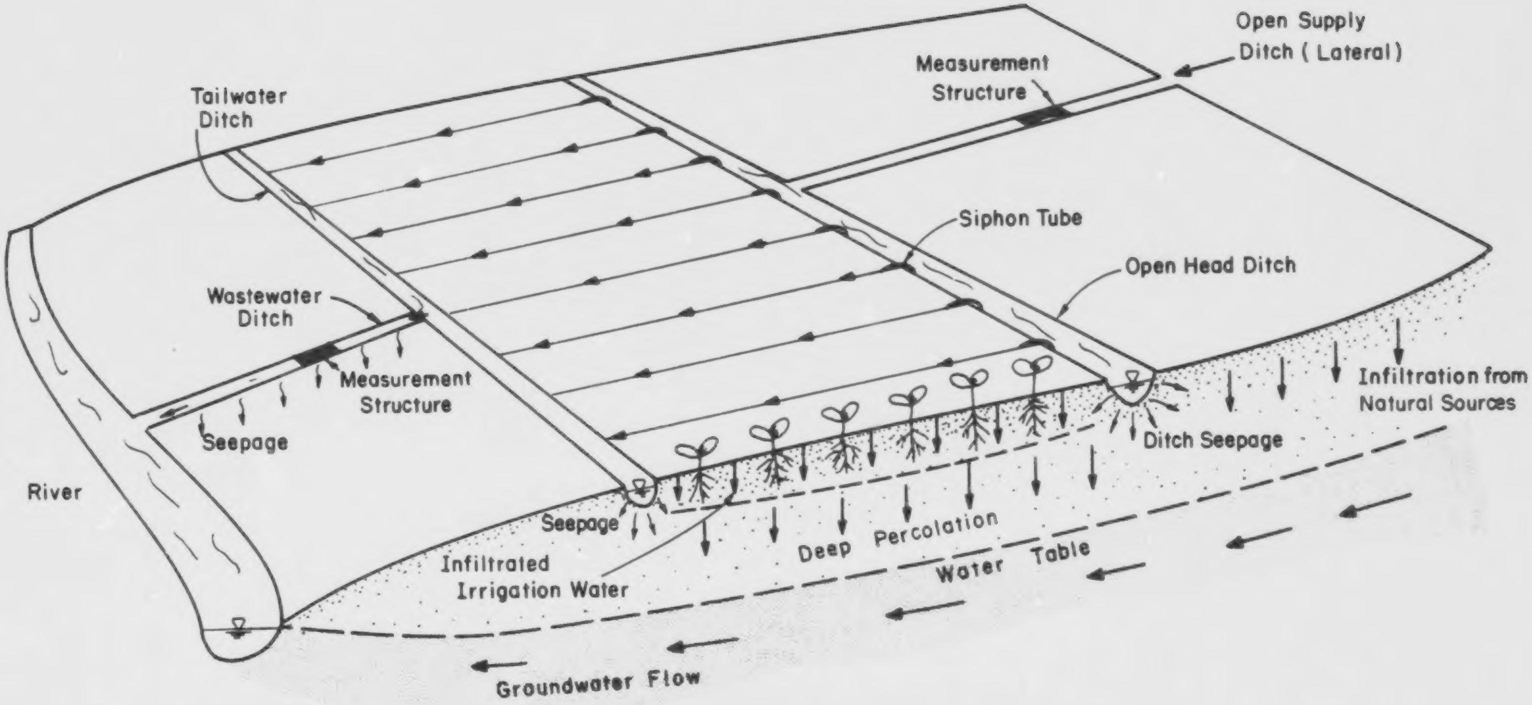

Open Supply
Ditch (Lateral)
Measurement
Structure
Tailwater
Ditch
Siphon Tube
Open Head Ditch
Wastewater
Ditch
Measurement
Structure
Seepage
River
Infiltration from
Natural Sources
Ditch Seepage
Seepage
Infiltrated
Irrigation Water
Deep Percolation
Water Table
Groundwater Flow

Figure 25. Schematic representation of the many parameters that must be considered in on-farm hydrosalinity investigations.

The subsurface component of the water removal subsystem and the hydro-salinity model generally is much more difficult to define than the surface portion. Much of the data needs to be evaluated indirectly rather than by direct means such as flow measurement. There are three main components of the subsurface water removal subsystem budget that must be determined. These are groundwater flows to the area, ditch seepage, and deep percolation contributions from agriculture, and consumptive use by phreatophytes. Deep percolation losses and consumptive use are considered in Section 8.

In some areas, septic tank leach fields and urban landscape irrigations contribute substantially to the groundwater flows. Some municipalities and industries may purposely inject water for storage or disposal. In areas where groundwater is pumped for municipal or irrigation purposes, the hydrology can become very complicated in attempting to define both the surface and groundwater segments. Groundwater inflows are usually determined by the use of wells, piezometers and various aquifer tests to determine the rate and quantities of these flows. There are numerous references on groundwater hydrology that include McWhorter and Sunada (1977); Welton (1970); Todd (1960) and Glover (1974) and others.

Hydro-Salinity Models

Salinity problems from irrigated agriculture generally result from subsurface return flows. The capability of a hydro-salinity model to provide necessary information for arriving at technological solutions is, therefore, dependent on the accuracy of groundwater field data and analysis. A problem often encountered during preparation of water and salt budgets is the reliability of the measured data. Usually, the precision of measurement varies with the scope of the investigation and the area under study. Since the hydrologic system is difficult to monitor and predict, it is impractical to expect models to operate without applying some adjustments in order that all components will balance. The budgeting procedure is defined as a weighting of the contributing factors in water and salt flows until all parameters represent the closest possible approximation of the conditions of the area. A schematic diagram of a general hydro-salinity model is shown in Figure 26. Oster and Wood (1977) discussed the sensitivity of some hydro-salinity models to various input parameters.

One of the early steady-state hydro-salinity models was developed by Walker (1970) and applied to the Grand Valley of western Colorado. The following description of the respective components of this model sufficiently describes the principles used in similar models, a few of which are referenced later.

Cropland Diversions--

Diversions to the croplands are accounted for by simple numerical budgeting procedures. The water flows are divided into several categories depending on the physical constraints of the system. For example, gravity irrigation supply is usually diverted by means of diversion dams. It is then conveyed through irrigated lands with water being lost by seepage, spilled into wasteways, evaporation, and discharged through turnout structures

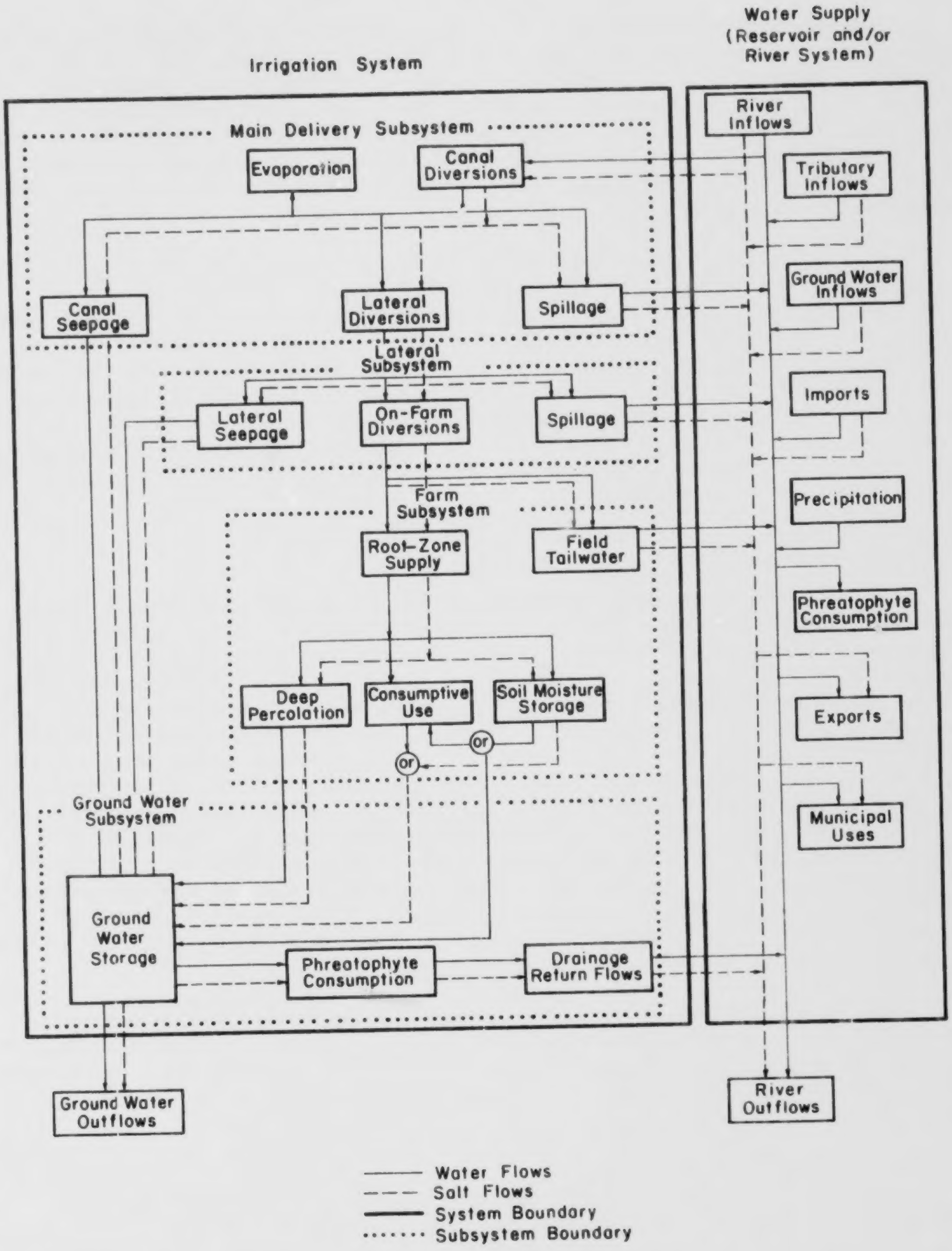

Water Supply (Reservoir and/or River System)
Irrigation System
Main Delivery Subsystem
Evaporation
Canal Diversions
Canal Seepage
Lateral Diversions
Spillage
Lateral Subsystem
Lateral Seepage
On-Farm Diversions
Spillage
Farm Subsystem
Root-Zone Supply
Field Tailwater
Deep Percolation
Consumptive Use
Soil Moisture Storage
or
or
Ground Water Subsystem
Ground Water Storage
Phreatophyte Consumption
Drainage Return Flows
Ground Water Outflows
River Inflows
Tributary Inflows
Ground Water Inflows
Imports
Precipitation
Phreatophyte Consumption
Exports
Municipal Uses
River Outflows
Water Flows
Salt Flows
System Boundary
Subsystem Boundary

Figure 26. Schematic of a generalized hydro-salinity model (Walker, 1970).

into laterals or farm supply ditches. Canal regulations by spillage may be facilitated by wasteways such as natural washes and man-made drains which may be located throughout the irrigated lands. These wasteways may also serve as outlets for subsurface return flows. Diversions into the lateral system are also reduced by seepage. Evaporation from canal and lateral surfaces is usually insignificant.

Root-Zone Flows--

The goal of irrigation is to recharge the soil-moisture of the root-zone with sufficient water to meet the needs of the crop until the next irrigation. Irrigation also serves to maintain an acceptable salt concentration in the root-zone. As described previously, overirrigation produces high water tables (waterlogging) and salinity problems in many areas. The root-zone submodel makes a detailed examination of the various flows occurring within the root-zone in order to quantify the salinity problem.

The important water movements within the root-zone are evapotranspiration and deep percolation, with water storage changes also occurring. Separation of these flows to take measurements on a large scale is impractical. Consequently, empirical computational methods are employed. The model described herein accounts for these basic water and salt flows by a budgeting process. The operation of this model assumes that irrigations are applied uniformly over each acre of cropland. Phreatophyte vegetation in the area is assumed to extract water only from groundwater flows or only use natural precipitation which falls on the area occupied by these plants. A generalized flow chart of the root-zone budgeting procedure is presented in Figure 27.

Several methods for estimating evapotranspiration can be used in this model. The locally calibrated Blaney-Criddle Method has provided an acceptable degree of accuracy for many studies. The Jensen-Haise Method and the Penman Method are more precise but require more climatological data.

With the evapotranspiration data and field measurements of moisture holding capacity, infiltration rates, and rooting depths, the budgeting scheme proceeds with computation of deep percolation losses from the root-zone. Calculations are initiated by assuming the crops use soil-moisture at the potential rate until the wilting point is reached, assuming that there are no adverse effects on the plant due to crop stress. The calculated potential consumptive use is limited to the water added by irrigation and the existing available soil-moisture storage. If irrigation water added to the root-zone is insufficient to meet demands of the crop, but storage of soil-moisture is sufficient to make up the difference, the need for water is satisfied. The assumption is also made that no deep percolation occurs while the available soil-moisture storage level is below field capacity, and that deep percolation and leaching occurs above this value. If the total available moisture for the period between irrigations is insufficient to meet the total demand, the crops use all water available. A term called "consumptive use deficit" is defined as the difference between potential and actual utilization.

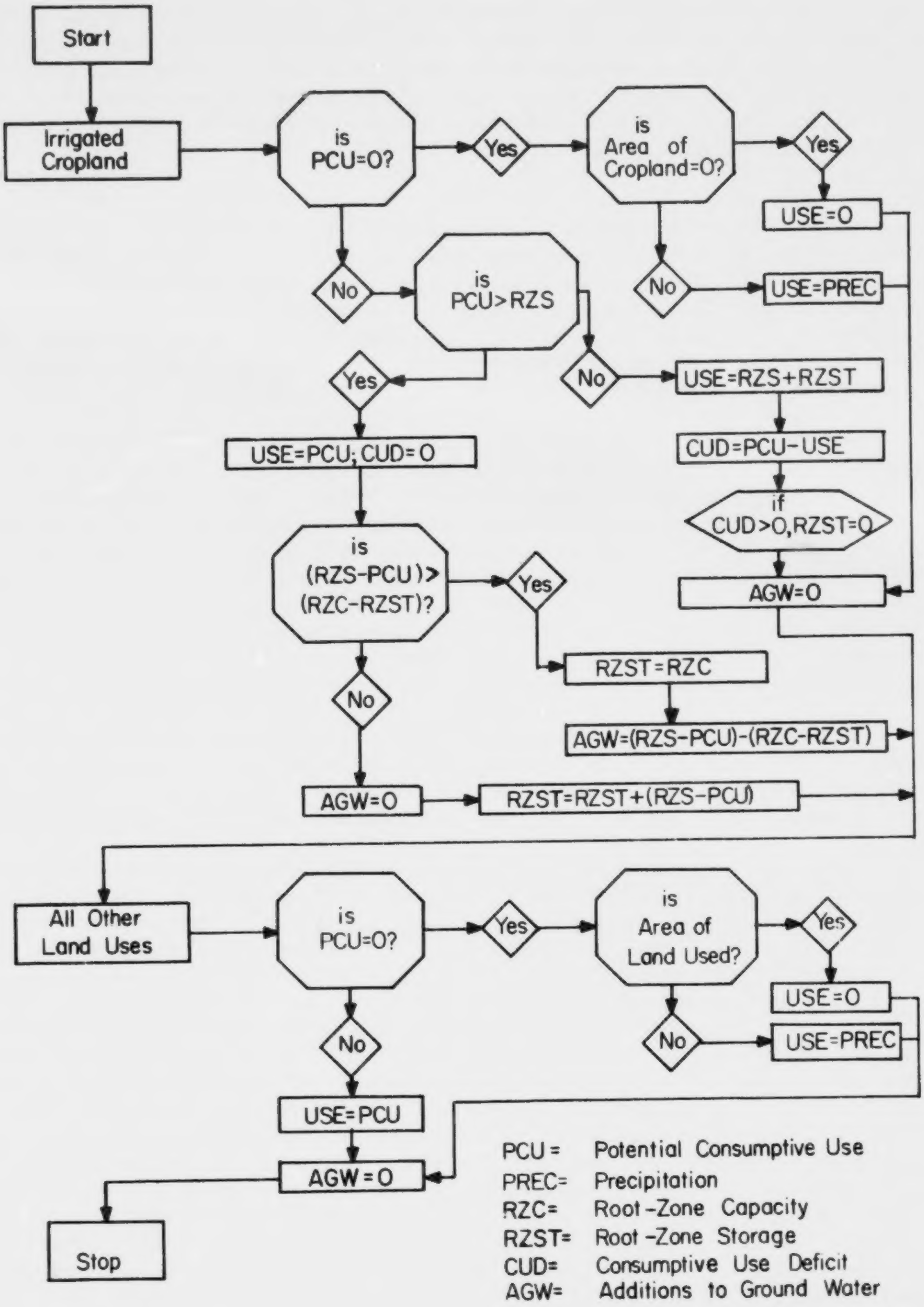

Start
Irrigated Cropland
is PCU=0?
Yes
is Area of Cropland=0?
Yes
USE=0
No
USE=PREC
No
is PCU>RZS
Yes
No
USE=RZS+RZST
CUD=PCU-USE
if CUD>0,RZST=0
AGW=0
USE=PCU; CUD=0
is (RZS-PCU)> (RZC-RZST)?
Yes
RZST=RZC
AGW=(RZS-PCU)-(RZC-RZST)
No
AGW=0
RZST=RZST+(RZS-PCU)
All Other Land Uses
is PCU=0?
Yes
is Area of Land Used?
Yes
USE=0
No
USE=PREC
No
USE=PCU
AGW=0
Stop
PCU = Potential Consumptive Use
PREC= Precipitation
RZC= Root-Zone Capacity
RZST= Root-Zone Storage
CUD= Consumptive Use Deficit
AGW= Additions to Ground Water

Figure 27. Illustrative flow chart of the root-zone budgeting procedure (Walker, 1970).

Salts in the water applied to the crops move into the root-zone where they become concentrated by evapotranspiration. The behavior of specific ions is complex and has not been considered in this particular model, but is discussed in Section 7.

Groundwater Model--

Most of the water in the soils and shallow groundwater aquifers originate as seepage from canals and laterals, deep percolation from the irrigation of croplands, and tributary subsurface inflows. Groundwater discharges eventually reach a local river or stream as surface drainage interception or subsurface return flows. The flows in the surface drainage system can be measured by installing flow measuring devices at the outflow points. Subsurface return flows are estimated from water table elevation data, the hydraulic gradients and the estimated hydraulic conductivities of the aquifer. It should be noted that in any hydro-salinity model, these estimated hydraulic conductivities contain the largest potential for error. Therefore, considerable effort must be made to properly evaluate the necessary parameters in the groundwater computations. For purposes of this model, Darcy's steady-state equation is used,

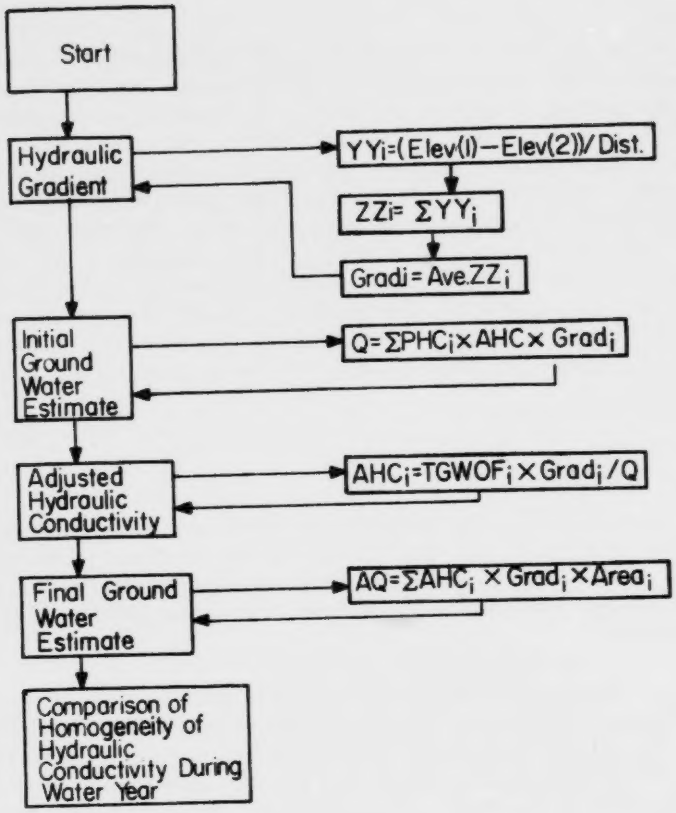
$$Q = AK \frac{dh}{dx} \tag{10}$$

in which Q is the discharge, A is the cross-sectional area of flow, K is the saturated hydraulic conductivity, and dh/dx is the hydraulic gradient in the direction of flow. Transient groundwater flows can be evaluated by other procedures such as those developed by Glover (1974 and 1975), and Morel-Seytoux and Daly (1975).

The groundwater analysis used in the Walker model, illustrated in Figure 28, starts by comparing the values for subsurface return flow, obtained from a mass balance of the area, to values obtained by computer calculation which uses field data. Therefore, two estimates of the subsurface return flows are formulated. The model is then adjusted until both methods yield the same values, thus obtaining a satisfactory alignment between the hydrologic and salinity parameters if no significant sources or sinks have been overlooked. Because the model only focuses on the relative magnitude of hydraulic conductivities, only the relative cross-sectional areas of the strata are important. The width can be any convenient value. The values for cross-sectional areas can be adjusted and used with the known hydraulic conductivities which are only known for selected points in the aquifer. The model adjusts the values of strata hydraulic conductivity until both estimates of the flows are equal. Since this is done on a monthly basis, the model calculates 12 values of hydraulic conductivity yearly for each strata. When adjustments in the model finally result in homogeneous annual values of hydraulic conductivity, the model represents the "best fit" between monitored and estimated data.

Available Models--

In addition to the hydro-salinity model reported by Walker (1970), several other models may be utilized. Hillel (1977) presented a simulation model that evaluates precipitation, infiltration, runoff, evapotranspiration,


Start
Hydraulic Gradient
$YY_i = (Elev(1) - Elev(2)) / Dist.$
$ZZ_i = \Sigma YY_i$
$Grad_i = Ave. ZZ_i$
Initial Ground Water Estimate
$Q = \Sigma PHC_i \times AHC \times Grad_i$
Adjusted Hydraulic Conductivity
$AHC_i = TGWOF_i \times Grad_i / Q$
Final Ground Water Estimate
$AQ = \Sigma AHC_i \times Grad_i \times Area_i$
Comparison of Homogeneity of Hydraulic Conductivity During Water Year

i = Refers to ith Strata
Grad. = Hydraulic Gradient
Q = Computed Ground Water Outflow
PHC = Field Values of Hydraulic Conductivity
AHC = Adjusted Values of Hydraulic Conductivity
TGWOF = Total Ground Water Outflow from Mass Balance Analysis
AQ = TGWOF

Figure 28. Flow chart of the groundwater modeling procedure (Walker, 1970).

deep percolation, capillary rise from the water table, and groundwater drainage of an agricultural field.

A similar model was designed by Makkink and Van Heemst (1975). The chemical quality aspects of irrigation return flows are simulated in models by Shaffer et al. (1977), the United States Department of the Interior, Bureau of Reclamation (1977), Crawford and Donigian (1973), and Hill et al. (1973). A summary of these models including the input requirements, time and spatial scales, computer structure, mathematical approach, and their acquisition is given in Appendix A. Most of these models include more modeling than is necessary for planning purposes. In all cases, salinity is only one aspect of these models.

SECTION 7

SOIL MOISTURE--CHEMISTRY SIMULATION

Detailed simulations are used to provide refinement to the hydro-salinity models primarily in the temporal prediction of root-zone and deep percolation salinities. These calibrated models can locally predict the quantity and quality of the leachate with respect to time. They can also quantify the effects of reducing irrigation return flows and the corresponding reductions in salinity. Their most valuable purpose is to establish the functions relating groundwater or deep percolation quantities and salt loading. In effect, such models are microscale hydro-salinity models that consider individual chemical reactions, the ionic constituents and the water flow system.

Since almost every area is unique, the models must be applied with care. Model use depends on a thorough understanding of the model capabilities and limitations. For example, many models were formulated to handle certain types of chemical systems; and, if the governing chemical process should happen to be different in a new area, the model cannot be used without adjustment. Successful application of the proper model requires an adequate data base, and the exact form of the data needed will often be different for each model. The type of data available may influence the selection of the model to be used. Detailed models will usually handle a combination of saturated and unsaturated flow conditions as well as the governing chemical reactions. McNeal (1974) examined soluble soil salts and their relationships to soil water movement.

Soil moisture-chemistry investigations should include consideration of the movement of salts or dissolved constituents, as well as the displacement of the solvent (water). Biggar and Nielsen (1967) stated:

> ...such considerations become particularly important in irrigated agriculture when it is desirable to know the concentration and location of a dissolved constituent in the soil profile, the reactions of constituents with each other and the soil matrix during the displacement and transport of water and solutes to plant roots.

It is important to establish some of the more important physio-chemical processes occurring in the soil which cause changes in the irrigation water as it moves through the root-zone. For example, it is necessary to consider the ion exchange and its relationship to the relative proportions of ions in the adsorbed phase and the solution phase. The precipitation and dissolution of slightly soluble salts can also be affected by the composition concentration of the soil-water solution and the partial pressure of carbon dioxide gas in the soil. The spatial variability of soils and the transport and mixing of the resident soil solution with the infiltrated irrigation water will also have a significant impact on the soil-water chemistry.

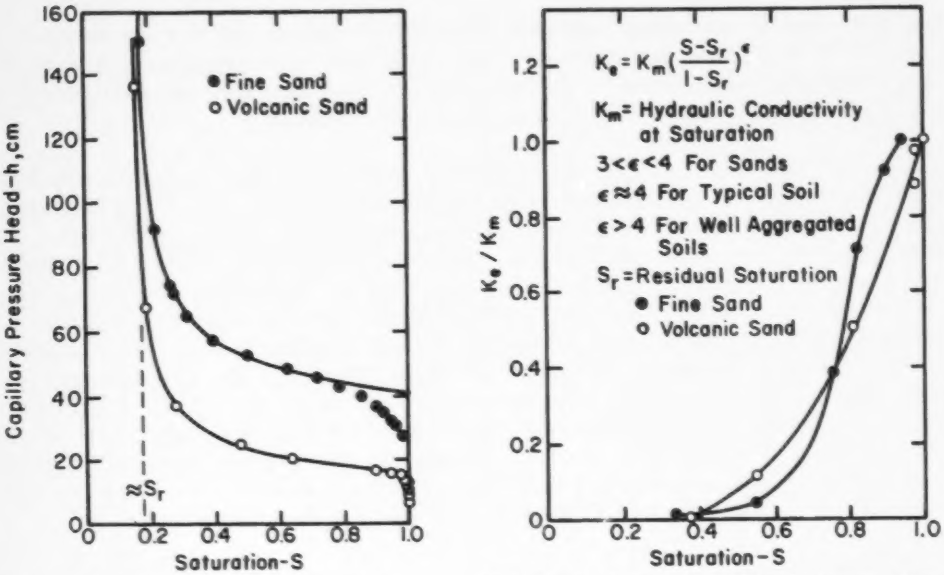
Much of the information on soil hydraulic properties required for the different models is included in the root-zone diversions, infiltration functions, initial soil-moisture conditions, field capacity, which is also referred to as residual saturation, permanent wilting point, bulk densities, and porosity of the various soil layers. It is necessary to establish the hydraulic conductivity-moisture content-capillary pressure relationships which are collectively referred to as the hydraulic properties of the soil (Figure 29). Additional chemical information required includes the respective concentrations of various ions in the soil-water solution, soil temperature with depth, and characteristic chemical reactions of the dominant ions which may include nitrogen, sulfates, carbon compounds and others that are typical of that particular soil chemistry system. Most of these data must be determined by thorough laboratory analyses of field soil and water data.

MODELING CONSIDERATIONS

The hydro-salinity models generally describe the existing water and salt flow conditions in an agricultural area. Many methods for predicting the reduction in salts returning via the groundwater to the river as an outcome of salinity control measures assume a one-to-one relationship between water and salt flows. For example, when subsurface return flows are reduced by 50 percent, it is assumed the salt pickup is also reduced by 50 percent. This is a poor assumption since this is not always the case. It is usually necessary to perform a soil moisture-chemistry simulation to arrive at the correct relationships between the volume of return flows and the mass emission of salt.

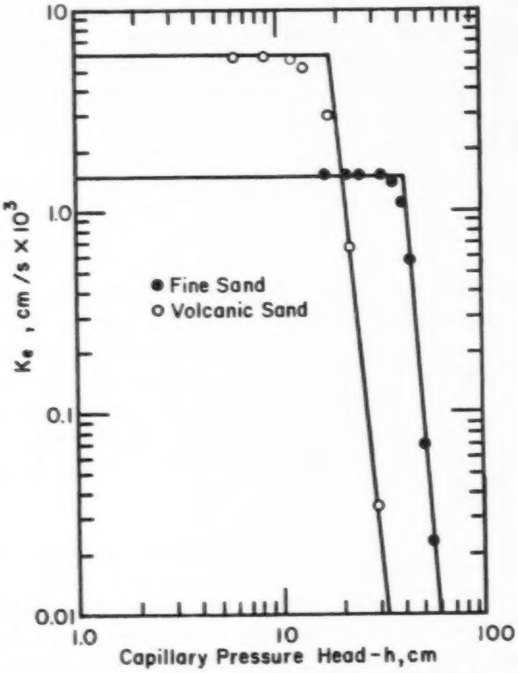
The primary objective of soil moisture-chemistry simulation is to model the transport of salts through the soils. The first portion of the flow of water and consequent transport of salts is through the root-zone which is usually partially saturated. A transient model of the moisture flow and chemical and biological reactions occurring in the root-zone was developed by Shaffer et al. (1977) and is described in Appendix A. An examination of this model illustrates the principal concepts in the detailed simulation level of irrigation return flow modeling.

The Shaffer Model consists of three separate programs. The first program describes soil-moisture movement and distribution with time. The second program interfaces the soil-moisture movements with a chemical-biological model to reconcile differences in the soil layers used in the calculations of soil moisture and chemistry. The third program computes the chemical and biological activity occurring in the soil profile. Figure 30 shows a block diagram of the overall model. A brief description of the moisture flow and chemical-biological models is included as a basis for understanding the data collection requirements.



(a) Typical Relationship between Capillary Pressure Head and Saturation.

(b) Typical Relationship between Effective Hydraulic Conductivity (K_e) and Saturation.



(c) Typical Relationship between Effective Hydraulic Conductivity (K_e) and Capillary Pressure Head.

Figure 29. Typical relationships defining the hydraulic properties of a soil (Brooks and Corey, 1964).

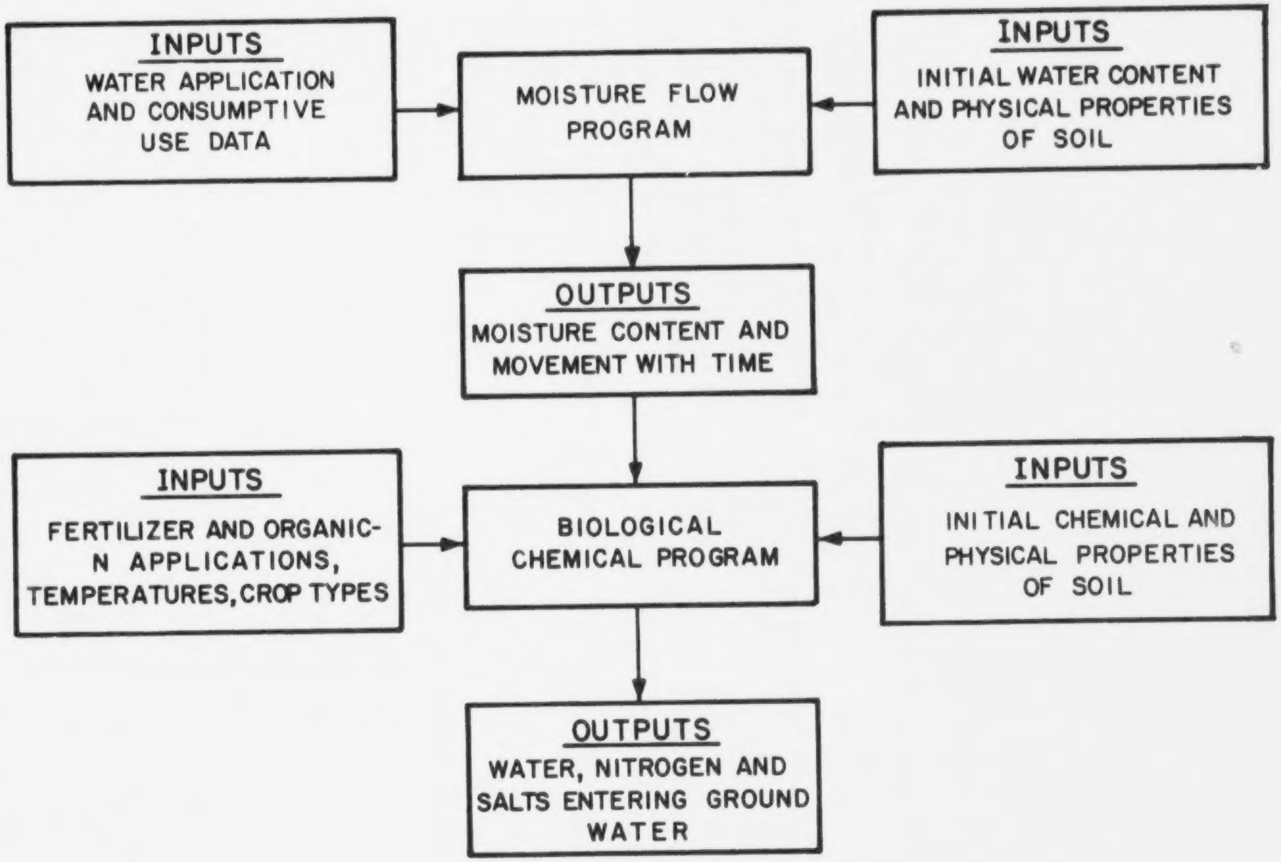

INPUTS
WATER APPLICATION AND CONSUMPTIVE USE DATA
MOISTURE FLOW PROGRAM
INPUTS
INITIAL WATER CONTENT AND PHYSICAL PROPERTIES OF SOIL
OUTPUTS
MOISTURE CONTENT AND MOVEMENT WITH TIME
INPUTS
FERTILIZER AND ORGANIC-N APPLICATIONS, TEMPERATURES, CROP TYPES
BIOLOGICAL CHEMICAL PROGRAM
INPUTS
INITIAL CHEMICAL AND PHYSICAL PROPERTIES OF SOIL
OUTPUTS
WATER, NITROGEN AND SALTS ENTERING GROUND WATER

Figure 30. Generalized block diagram of the model (Dutt et al., 1972).

The flow is one-dimensional and was developed using Richard's equation with a sink term. The model is schematically defined in Figure 31. Mathematically, flow is described by the diffusivity form of the Richard's equation:

$$\frac{\partial\theta}{\theta\tau} = \frac{\partial}{\partial x} \left(\frac{D\partial\theta}{\partial x} - K\right) - S \qquad (11)$$

where θ = volumetric water content

τ = time

x = length

K = hydraulic conductivity

S = sink term; and

D = diffusivity.

The sink term S is computed using the Blaney-Criddle equations for evapotranspiration although other equations can be adapted to the model. Loss due to evapotranspiration is distributed through the soil profile by assuming a specific root distribution for the crop. The root distribution and coefficients for the Blaney-Criddle equations are supplied by the user. When known, actual values of evapotranspiration can be used in the sink term.

Salt transport in one dimension is described by the following equation:

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial z} \left(D \frac{\partial c}{\partial z}\right) - \nu\frac{\partial c}{\partial z} \qquad (12)$$

where c = solute concentration

t = time

D = hydrodynamic dispersion coefficient

z = depth; and

ν = seepage velocity (Darcy velocity divided by porosity).

By assuming the term $\frac{\partial}{\partial z}\left(D \frac{\partial c}{\partial z}\right)$ is negligible compared to $\nu\frac{\partial c}{\partial z}$, the equation reduces to $\frac{\partial c}{\partial t} = -\nu\frac{\partial c}{\partial z}$. This assumption implies that transport due to diffusion in partially saturated soils is negligible as compared to the convective transport. The model computes the moisture flow (ν) and couples flow with chemical changes $\frac{\partial c}{\partial z}$ computed in the biological-chemical program to provide the salt transport rate. This technique is called a mixing cell concept.

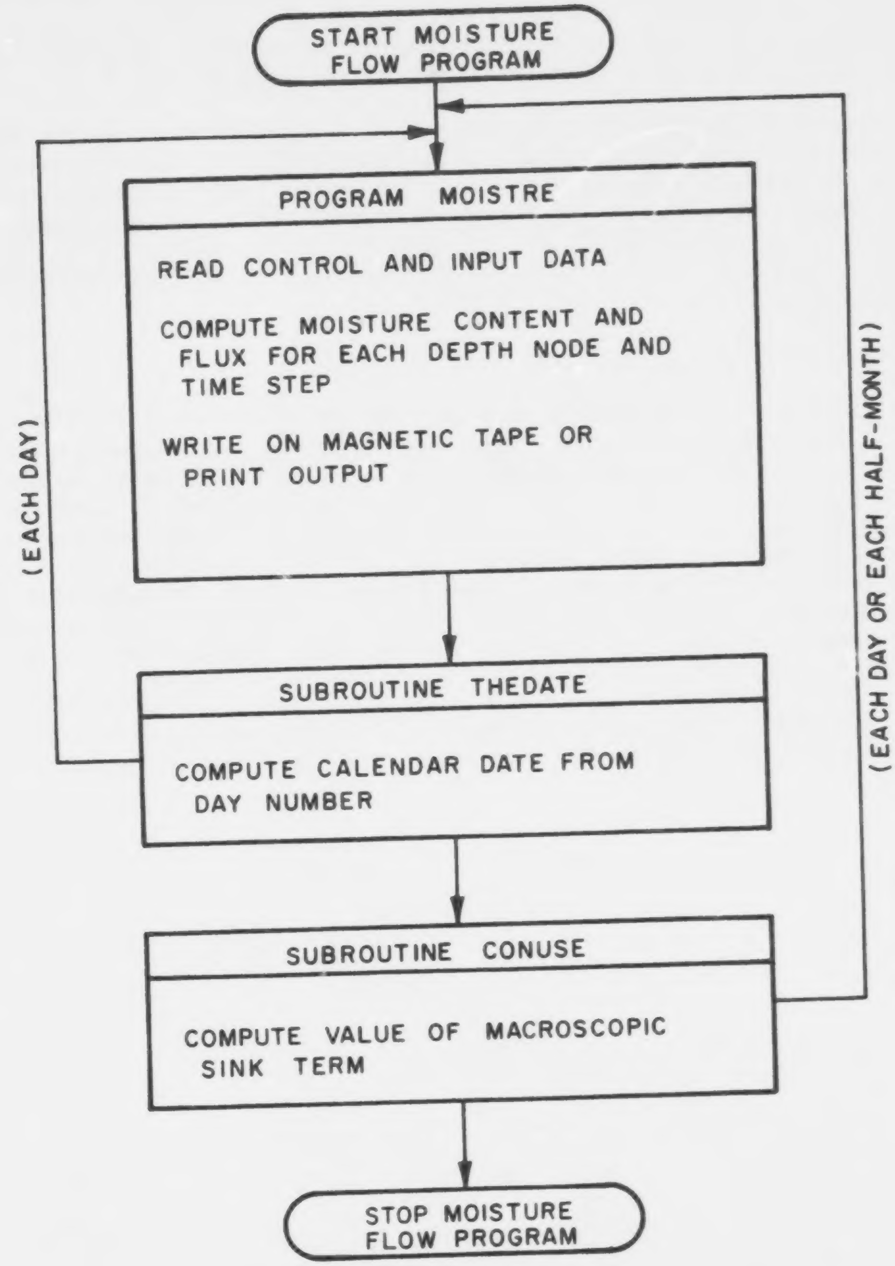

START MOISTURE FLOW PROGRAM
PROGRAM MOISTRE
READ CONTROL AND INPUT DATA
COMPUTE MOISTURE CONTENT AND FLUX FOR EACH DEPTH NODE AND TIME STEP
WRITE ON MAGNETIC TAPE OR PRINT OUTPUT
(EACH DAY)
(EACH DAY OR EACH HALF-MONTH)
SUBROUTINE THEDATE
COMPUTE CALENDAR DATE FROM DAY NUMBER
SUBROUTINE CONUSE
COMPUTE VALUE OF MACROSCOPIC SINK TERM
STOP MOISTURE FLOW PROGRAM

Figure 31. Generalized block diagram of moisture flow program (Dutt et al., 1972).

The chemical exchange model computes the equilibrium chemistry concentrations for calcium, magnesium, sodium, bicarbonates, carbonates, chlorides, and sulfates. The nitrogen chemistry, including ammonium, nitrates, and urea-nitrogen, uses a kinetic instead of an equilibrium approach. A block diagram of the biological-chemical model is given in Figure 32.

Once the necessary field data are collected, equations can be developed to predict the variation in chemical quality, including ionic constituents of water in the soil profile. The salt pickup or salt precipitation resulting from movement of subsurface irrigation return flows is also determined. These results, when combined with the hydro-salinity model, allow an evaluation of various salinity control measures for reducing salinity reaching the groundwater and returning to the river.

Other Available Models

In addition to the highly detailed simulation model by Shaffer et al. (1977), there are several simple models that may be quite appropriate for a planning study. One of the more complete irrigation hydrology models is presented by Gupta et al. (1977). This model gives a fairly complete water budgeting procedure for the region between the crop canopy and the water table. The most important feature of this method is its flexibility. The authors provided the capability to use several analytical approaches for major segments of the program. While the model does not consider water quality, the model could be coupled with salinity models reported by Oster and McNeal (1971), Rai and Franklin (1973), Tanji et al. (1972), and Saxton et al. (1977). Models by DeWit and Van Keulen (1975), Frissel and Reiniger (1974), Margheim (1967), and Melamed et al. (1977) encompass both the irrigated hydrology and the quality of return flows on a detailed level.

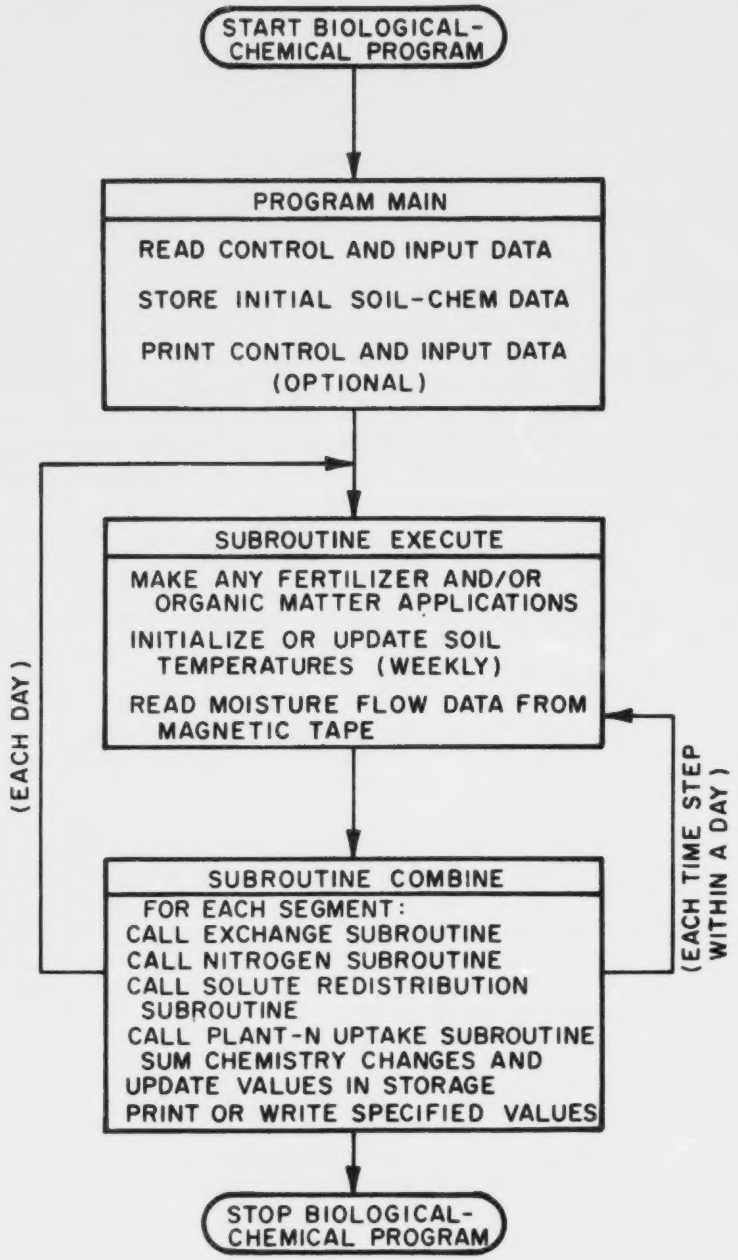

START BIOLOGICAL-CHEMICAL PROGRAM
PROGRAM MAIN
READ CONTROL AND INPUT DATA
STORE INITIAL SOIL-CHEM DATA
PRINT CONTROL AND INPUT DATA (OPTIONAL)
SUBROUTINE EXECUTE
MAKE ANY FERTILIZER AND/OR ORGANIC MATTER APPLICATIONS
INITIALIZE OR UPDATE SOIL TEMPERATURES (WEEKLY)
READ MOISTURE FLOW DATA FROM MAGNETIC TAPE
(EACH DAY)
(EACH TIME STEP WITHIN A DAY)
SUBROUTINE COMBINE
FOR EACH SEGMENT:
CALL EXCHANGE SUBROUTINE
CALL NITROGEN SUBROUTINE
CALL SOLUTE REDISTRIBUTION SUBROUTINE
CALL PLANT-N UPTAKE SUBROUTINE
SUM CHEMISTRY CHANGES AND UPDATE VALUES IN STORAGE
PRINT OR WRITE SPECIFIED VALUES
STOP BIOLOGICAL-CHEMICAL PROGRAM

Figure 32. Generalized block diagram of a biological-chemical program (Dutt et al., 1972).

SECTION 8

FIELD INVESTIGATIONS

The purpose of field investigations is to determine and/or predict the results expected from various potential solutions. Evaluating the effectiveness of existing practices and methods provides insight into more efficient and economical operational methods which result in savings of labor, money, and water, and a better balance between crop returns and irrigation costs. The evaluation procedure provides direction to action programs for the reduction of nonpoint pollution from that area and similar areas.

Because many of the nonpoint parameters tend to be site specific, every irrigated area should be evaluated individually. The same conditions encountered in one area may produce different consequences in another. If the uniqueness of each area is recognized, it may be possible to apply data collected in one area to other areas. For example, much of the information gathered in the Colorado River Basin may be applied to irrigated areas in the Rio Grande and Arkansas River systems even though irrigation practices, cropping patterns, topography, soil types, and crops may differ. The methodology employed can certainly be made applicable to other areas under investigation.

This section is divided into three primary discussion areas: (a) delivery subsystem investigations; (b) farm subsystem investigations, and (c) water removal subsystem investigations. It should be realized that there is an overlap between these broad topics because many of the techniques apply to all three categories. Many of the methodologies discussed in this section apply to the collection of data for both hydro-salinity modeling and soil moisture-chemistry simulation.

This section is concerned with the analysis of the managerial and physical inputs to an irrigation system. It is often necessary to evaluate the economic, legal and sociological aspects of pollution control problems in the area. These analyses should establish the effects and costs of the proposed solutions, potential crop yields (increase or reduction), land costs (initial investments, preparation, seed, fertilizer), irrigation costs (labor, energy, maintenance), and existing crop yields as functions of an area, water quantity and costs. Interest rates, taxes, expected life of equipment, bank lending practices and availability of loans, and many other financial aspects of the area also need examination. Modifications to the existing institutional framework or establishment of one to adequately handle an implementation project must also be determined.

PROCEDURE

There are three basic steps that must be undertaken to evaluate nonpoint source pollution in any irrigated area. These are:

1. Establishment of the boundaries of the area to be studied;
2. Determination of whether there is a problem by using inflow-outflow analysis, where inflow minus outflow equals the change in storage; and
3. Determination of the source of the problem with a monitoring network and subsequent investigations of the delivery subsystem (canals and laterals), the farm subsystem (irrigation methods, cultural practices), and the water removal subsystem (type, reuse).

Obviously, these are broad categories and the depth to which these investigations are conducted depends on the cost and the degree of accuracy required for the study, as well as the limitations of the applications of the IRF Models including time frame requirements, data needs, and applicability to the situation.

Determination of the sources of the problem is the most time consuming and costly portion of the investigative procedure. This process is usually referred to as the hydro-salinity analysis, the methodology of which varies depending on the types of problems encountered. Regardless of the type of problem, the usual procedure is to instrument and investigate a small study area intensively, and to sample many of the important variables on the remainder of the irrigated lands not in the study area. Results are then extrapolated to the entire area. Careful selection of the area for intensive study must be done to ensure the area is large enough and contains soils, field conditions, irrigation methods, and other aspects that are representative of the larger area.

The boundaries of the study area are usually dependent on natural hydrologic characteristics such as hydrologic divides, watersheds, drainage systems, and the canal or lateral network. In the first step, the whole area is defined. During subsequent investigations, the boundaries may be incrementally reduced so only one farm or field is considered. In small areas, hydrologic conditions can be studied in detail, and the various segments of water and salt flow budgets can be isolated and more accurately measured.

DELIVERY SUBSYSTEM INVESTIGATIONS

Field investigation techniques that are particularly important in nonpoint source pollution control programs for the delivery subsystem are primarily quantity of flow and seepage measurements. Often, the importance of flow measurement is neglected in irrigated agriculture, but accurate measurement of surface water is required for water resource evaluations as well as for efficient water management, and irrigation return flow studies. Errors in flow measurement tend to be cumulative, and the end result can cause errors in excess of 100 percent of the real values. Accurate flow measurement is required in seepage measurement and various on-farm investigations.

Flow Measurement of Surface Water

Any person attempting to conduct a hydrological investigation should have a good understanding of the theory and methodology of various flow measurement techniques, including the limitations, advantages, and expected accuracy for each method. For example, weirs can not always be used in irrigated areas due to high hydraulic energy losses; Parshall or Cutthroat flumes should not be placed immediately below a culvert or other physical devices that cause nonuniform flow; and precalibrated propeller meters are accurate only for specified situations and can be severely affected by sediment.

Another consideration is that most flow measurement devices, particularly for open channel flow, give only the instantaneous rate of flow. If the flow rate changes, as is common with surface delivery systems, the use of an instantaneous measurement to calculate an irrigation application may easily result in errors of 20 percent or more. It is therefore usually necessary to obtain some type of a totalizing record of the flow.

Units of volume and of volume per unit time are the basic units required for water measurement in irrigated agriculture. The units of volume commonly used in agriculture are gallon, cubic foot and acre-foot, while the corresponding metric units are liters, cubic meters and hectare-meters. The common rates of flow in English units are gallons per minute, cubic feet per second, and Miner's Inch, which is defined by each state's legislation and varies from state to state. The common metric units are liters per second and cubic meters per second, or cubic meters per day.

During most hydrologic investigations, it is necessary to obtain a temporal history of water flow. There are numerous commercial devices available that provide continuous records for analysis, such as clock-driven water level recorders. Information on the installation and availability of such instruments can be obtained through the local office of the Water Resources Division of the United States Geological Survey or other federal and state water resource agencies.

There are numerous detailed references for surface water measurement techniques including the United States Bureau of Reclamation (1974), United States Geological Survey (1968-1978), Skogerboe et al., (1967a), Bos (1976), and Robinson and Humpherys (1967). An excellent theoretical description of flow measurement is presented by Troskolanski (1960). Thomas (1957) presents a good discussion on sources of error in flow measurements for irrigation. For purposes of discussion, flow measurement methods are divided into the three broad categories of velocity, hydraulic head, and other miscellaneous methods. Velocity methods include Pitot tubes and current meters, venturi meters, and propeller meters. Hydraulic head techniques include the Parshall, Cutthroat and trapezoidal flumes, as well as weirs and orifices. Other miscellaneous techniques include chemical salt and dye dilution, total count radioisotopes, magnetic and sonic methods.

Velocity Measurements--

Velocity determination may be made in open channels or in closed conduits with Pitot tubes (King and Brater, 1963). Pitot tubes can be calibrated to read the flow rate directly from one velocity measurement. One such device is known as the Cox meter. Another special form of the Pitot tube which is very useful in measuring pump discharges is the Collins flow gage (Figure 33). This device consists of an impact tube which is a straight small diameter brass tube inserted through a pipe. The tube is divided into two compartments, each with an orifice 180 degrees apart. One is called the impact orifice and is oriented to the upstream side, and the trailing orifice, is located on the downstream side. The differential head indicated on the air-water manometer is twice the velocity head, from which the discharge rate can be determined.

The determination of mean velocity and the calculation of discharges in open channel flows are usually done by methods such as current meter measurements. Current meters are instruments that employ an impeller which rotates at a speed proportional to the velocity of the flowing water. The cross-section of flow is divided into a number of subareas varying from 0.15 to 6 meters (0.5 to 18 ft.) in width, depending on the size of the stream and precision desired. It has been found that mean velocity readings taken at 0.2 and 0.8 of the depth below the surface is an accurate estimation of the average velocity in the vertical direction. Discharge is then determined by application of the continuity equation. Current meters are often used as the standard by which many other methods are calibrated, and depending on the type of equipment, skill and care of data collection, the current meter values are accurate. Any structure that has a constant cross-sectional area can be rated for use as a flow measuring device, and these ratings are usually established with a current meter. A typical set of rating curves is shown in Figure 34.

When a horizontal pipe, for example from a pump, discharges into the atmosphere, the discharge can be obtained using the trajectory of the jet which is a function of the velocity of discharge. The discharge of Q is given by the equation:

$$Q = CC_d \frac{AX}{\sqrt{Y}} \tag{13}$$

where C is the units conversion constant, C_d is the coefficient of discharge, A is the cross-sectional area of the pipe, and X and Y are the horizontal and vertical coordinates. Israelson and Hansen (1967) discuss this method in more detail as shown in Figure 35b.

A vane or pendulum type meter is a velocity measurement with a variable width vane that extends into the water of an open channel. Discharge is measured by calibrating the angular displacement of the vane.

Precalibrated propeller meters are made by a variety of manufacturers for velocity measurement in conduits where cross-sectional areas of flow remain constant with time (Figure 35a). These meters can be calibrated to read directly in cumulative volume and/or flow rate. Easily portable installations are also often used for pump or farm efficiency studies (Figure 36). Impeller meters can also be used, but tend to be much more expensive.

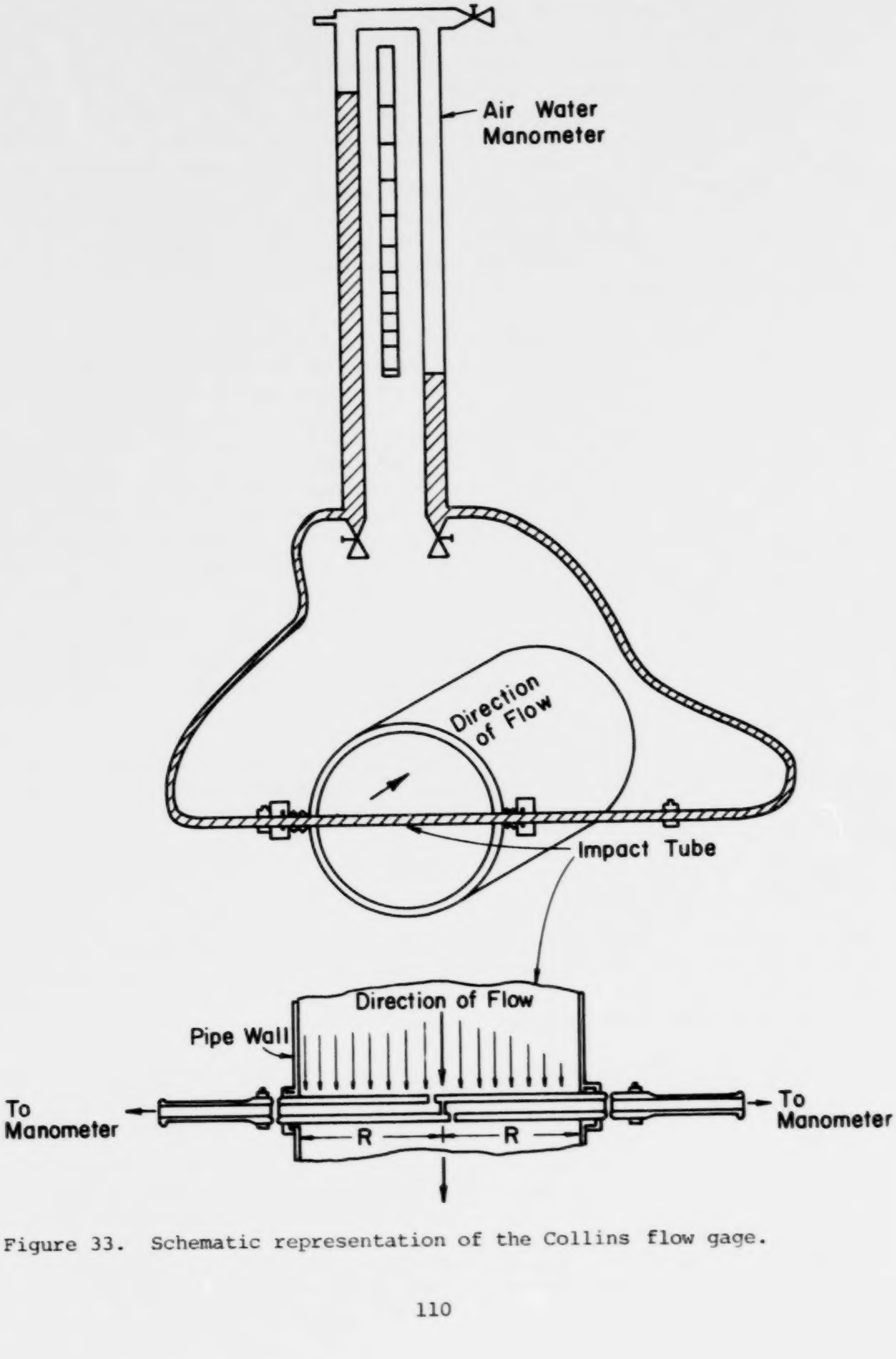

Air Water
Manometer
Direction
of Flow
Impact Tube
Direction of Flow
Pipe Wall
To
Manometer
To
Manometer
R
R

Figure 33. Schematic representation of the Collins flow gage.

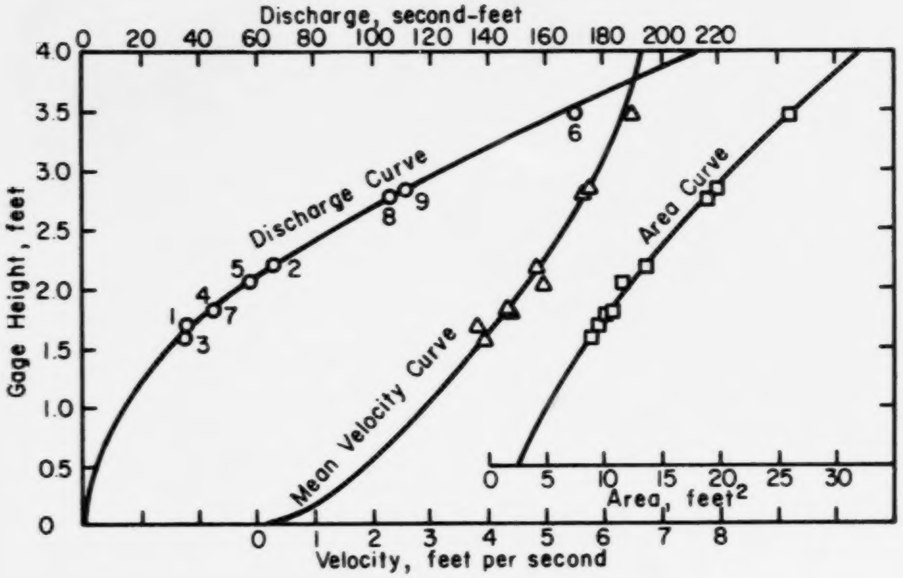
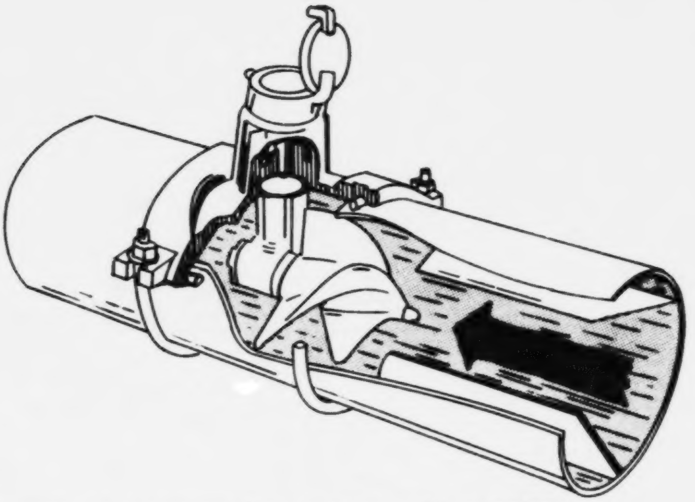
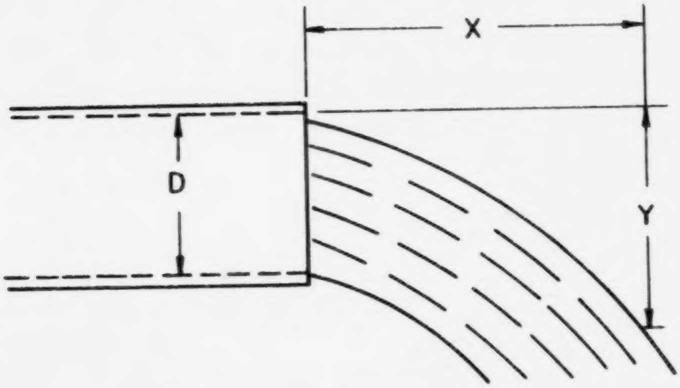


Figure 34. Typical rating curves for current meter measurements.



a) Sketch of a precalibrated propeller meter for use in closed conduits.



b) Trajectory method of determining discharge.

Figure 35. Trajectory method and propeller meters for measuring discharge.

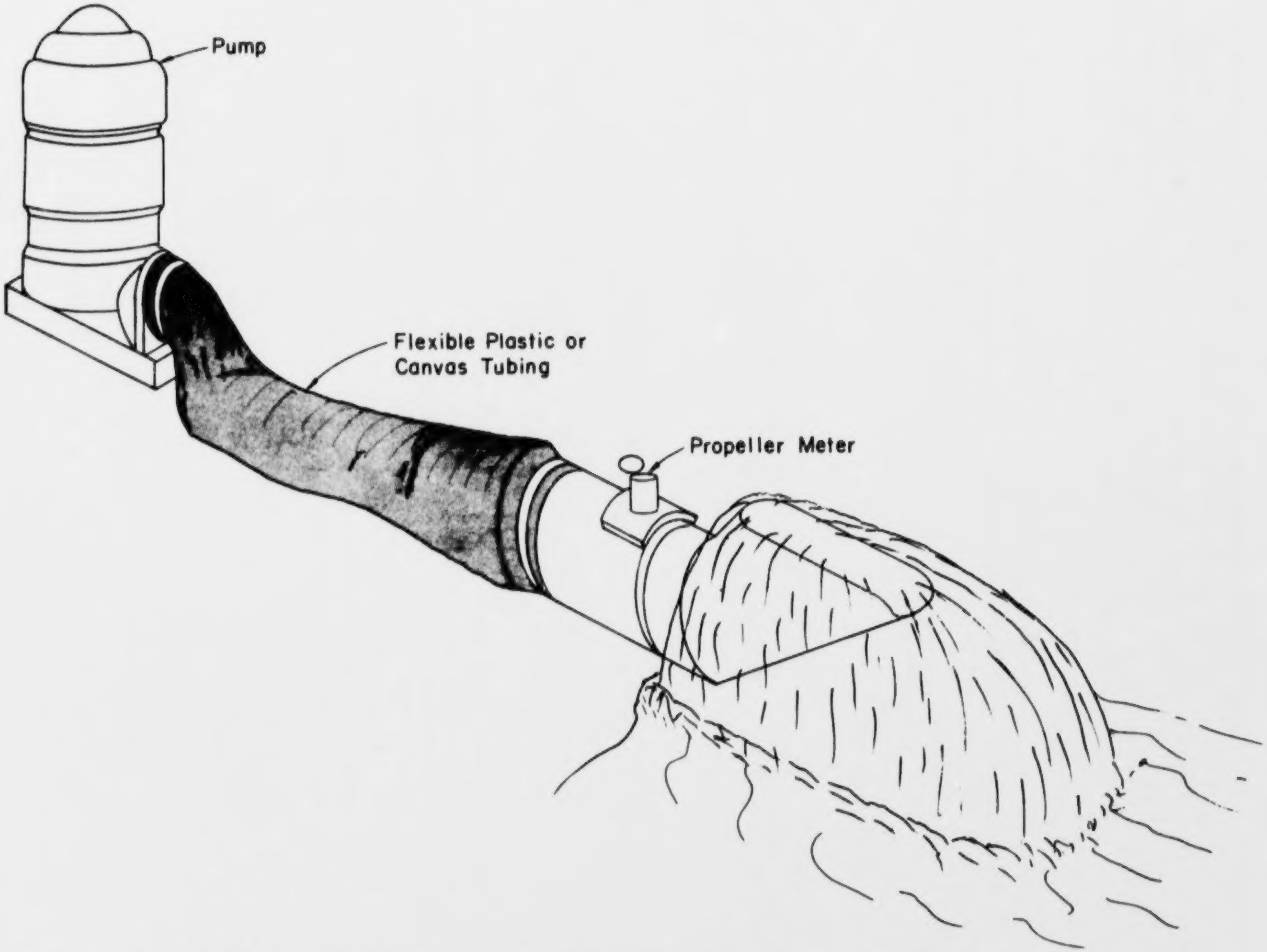

Pump
Flexible Plastic or Canvas Tubing
Propeller Meter

Figure 36. Portable installation of a propeller meter used to measure discharge from a pump for farm or pump efficiency studies.

Head Measurement Techniques

Hydraulic head measurement techniques employ the use of structures by which discharge is a function of the depth of water or head on the device. In other words, they have a consistent relationship between the hydraulic head and discharge. Most of these devices used in irrigated agriculture have standardized dimensions and known hydraulic characteristics. In open channel flow, weirs and flumes cause flow to pass through critical depth, and in closed conduits orifices are used.

A weir is a barrier that is placed in a channel to constrict the flow and cause it to fall over a crest (Figure 37). Weir openings can be rectangular, trapezoidal, triangular or other shapes to give specialized head-discharge relationships. Standard references such as King and Brater (1963) can be consulted for tables and specific discussions on weirs. Weirs working in submerged conditions are discussed by Skogerboe et al. (1967d) and Chesness et al. (1973).

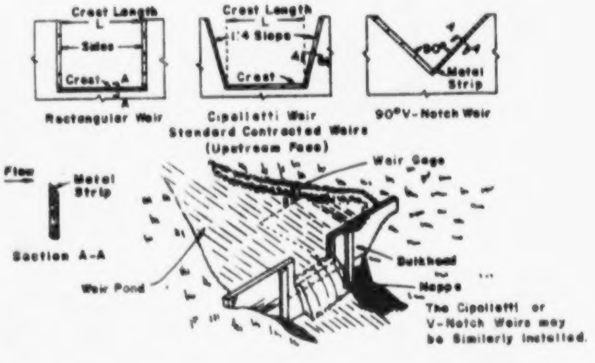
Generally, any specially shaped and stabilized channel section that constricts the flow is called a flume. Flumes are generally less inclined to catch floating debris and sediment than are weirs, and for this reason, they are well suited for measuring runoff or other waters with high sediment loads.

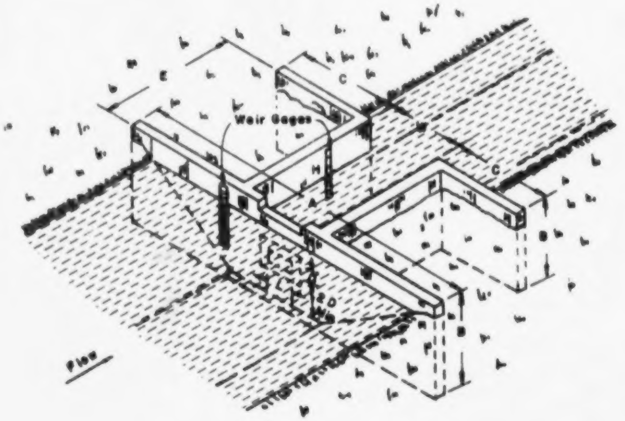
The most commonly used flume in the western United States is the Parshall flume (Figure 38b), which has been described by Parshall in several publications (1941, 1959, 1953); Robinson in 1959 and 1965; Caplan (1963); and the United States Bureau of Reclamation (1974). Submerged flow calibrations for the Parshall flume are presented by Skogerboe et al. (1967b).

Another type of flume gaining wide acceptance due to its inexpensive construction is the Cutthroat flume which can be built in a wide variety of throat width and flume length combinations to suit specific needs (Figure 38a). Design and installation information for free flow and submerged conditions is presented by Skogerboe et al. (1967c) and Skogerboe et al. (1973). The Cutthroat flume and Parshall flume have equivalent accuracy and require very low head losses for operation.

A flume adapted for widely fluctuating runoff measurements is known as the H-flume (Figure 38d), which is discussed by Frevert et al. (1966) and the United States Department of Agriculture (1962). Another type of flume which is well suited for small flows such as individual furrow flows is the trapezoidal flume (Robinson and Chamberlain, 1960; American Society of Agricultural Engineers, 1977), which is shown in Figure 38c.

King and Brater (1963) define an orifice as an opening with a closed perimeter through which water flows. An orifice with prolonged sides (2 or 3 pipe diameters in length) is called a tube. For orifice flow conditions to occur, the water surface upstream of the orifice must be well above the top of the opening. If the upstream depth drops below the top of the opening, it then conforms to the conditions of weir operation (United States Bureau of Reclamation, 1974). If the orifice is level with the floor of


Crest Length
L
Sides
Crest
A
A
Rectangular Weir
Crest Length
L
1:4 Slope
4
1
Crest
Cipolletti Weir
Standard Contracted Weirs
(Upstream Face)
90°
Metal Strip
90°V-Notch Weir
Flow
Metal Strip
Section A-A
Weir Gage
Weir Pond
Bulkhead
Nappe
The Cipolletti or
V-Notch Weirs may
be Similarly Installed.


Weir Gages
E
C
C
H
A
B
B
D
F
Flow

Orifice and Weir Formulas

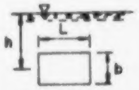
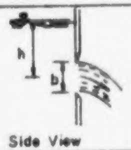
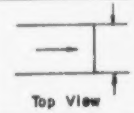
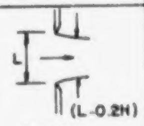
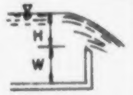
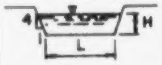
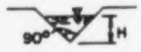
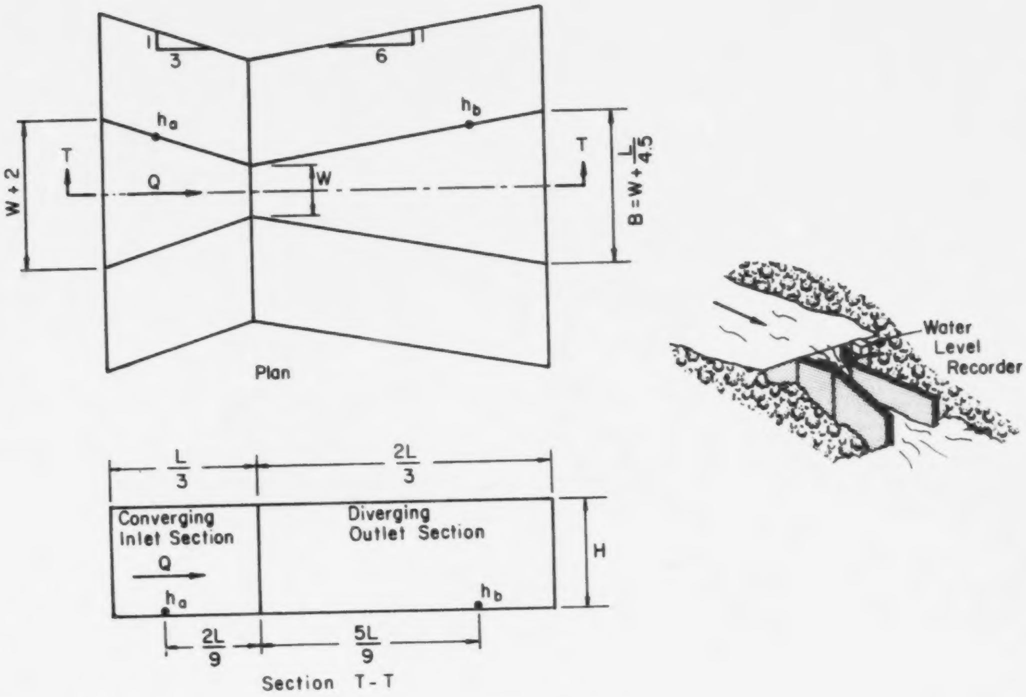
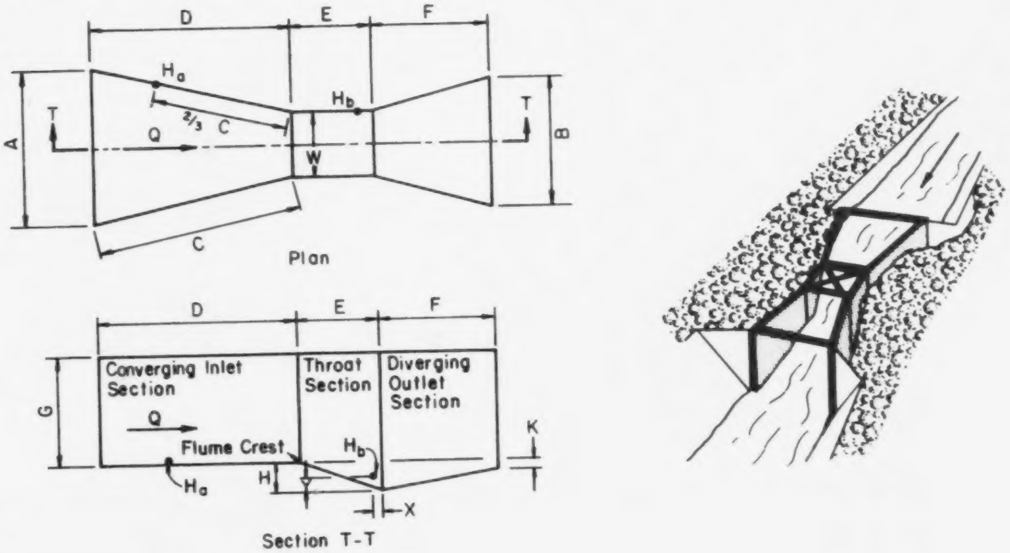
Measuring Device (All Sharp Crested)	Views		Formula
Orifice	 Front View	 Side View	$Q = 0.61 A \sqrt{2gh}$
Rectangular Weir (without Contraction)	 Top View		$Q = 3.33 L H^{3/2}$
Rectangular Weir (with Contraction)	 Top View	 Side View	$Q = 3.33 (L - 0.2H) H^{3/2}$
Trapezoidal Weir (Cipolletti)	 End View		$Q = 3.37 L H^{3/2}$
90° Triangular Weir	 End View		$Q = 2.49 H^{3/2}$

Figure 37. Schematic representation of various weirs used in agricultural water management.

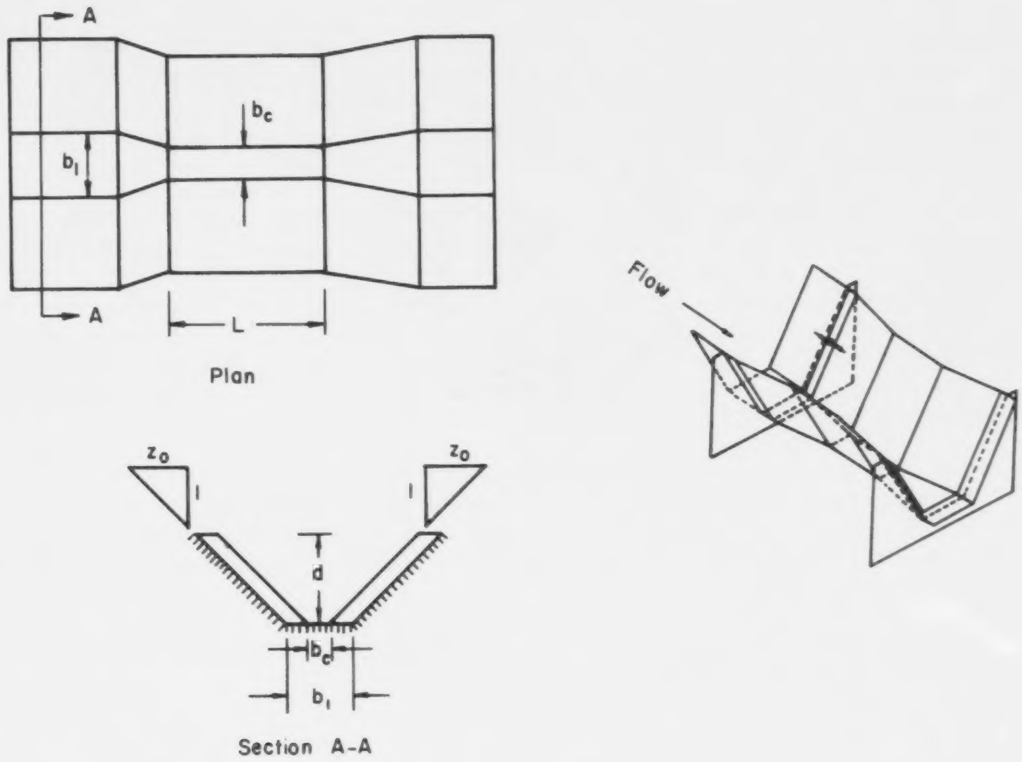

1
3
6
1
ha
hb
T
T
W + 2
Q
W
B = W + L/4.5
Plan
Water Level Recorder
L/3
2L/3
Converging Inlet Section
Diverging Outlet Section
Q
ha
hb
H
2L/9
5L/9
Section T-T

a) Cutthroat flume.

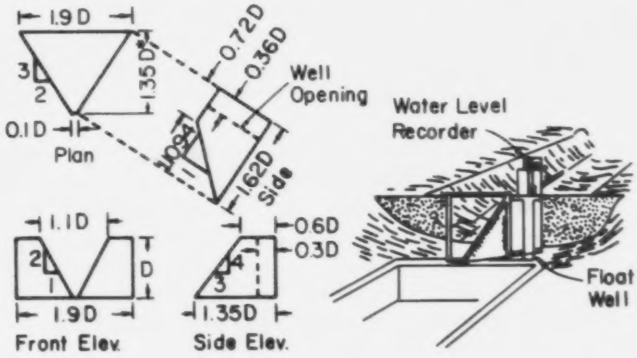

D
E
F
Ha
Hb
2/3 C
T
T
A
Q
W
B
C
Plan
D
E
F
G
Converging Inlet Section
Throat Section
Diverging Outlet Section
Q
Flume Crest
Hb
K
Ha
H
X
Section T-T

b) Parshall flume.

Figure 38. Schematic representation of some common types of flumes used in agricultural water measurement.


A
A
b_c
b_1
L
Plan
Flow
z_o
1
z_o
1
d
b_c
b_1
Section A-A

c) Trapezoidal flume.


1.9 D
3
2
1.35 D*
0.1 D
Plan
0.72D
0.36D
Well Opening
1.08D
1.62D Side
1.1 D
2
1
D
1.9 D
Front Elev.
0.6D
0.3D
4
3
1.35D
Side Elev.
Water Level Recorder
Float Well

*For D<1', Length is Greater than 1.35 D so as to Attach Float Well.

d) H-flume.

Figure 38.(continued).

a structure, it is called a gate or sluice; however, often these must be individually calibrated by use of a current meter. Orifices can be submerged with the exit jet under water or with free discharge directly to the atmosphere. These devices are often troubled with debris problems in agricultural situations.

A commonly used gate for controlling and measuring irrigation diversions to a lateral or farm is called the metergate. Basically, these are standard headgates that are calibrated to yield discharge as a function of the difference in static head between the canal and a point located 1/3 the pipe diameter behind the gate. These are sold commercially by several steel headgate manufacturers and calibration tables are usually furnished by these suppliers. Two common methods for measuring flows from headgates are illustrated in Figure 39.

Miscellaneous Measurement Techniques--

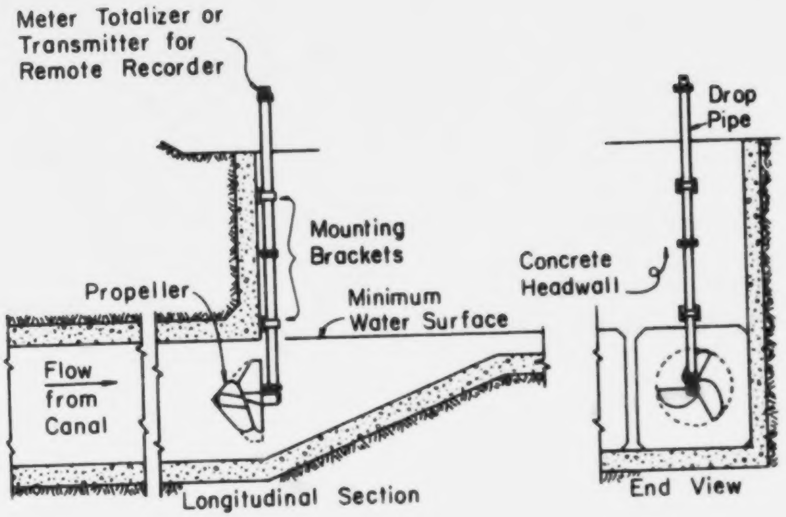
There are a multitude of flow measurement techniques that directly utilize velocity or head for discharge determinations. These include chemical dye and salt dilution methods, total count radioisotope, and magnetic and sonic techniques.

Salt dilution methods consist of adding a concentrated salt solution of known strength to a stream. By chemical analysis, the diluted concentration is determined after it has mixed completely with the water (United States Bureau of Reclamation, 1974). Dye dilution techniques are quite similar and the diluted concentration is determined by colorimetric analysis or fluorescent analysis (Liang and Richardson, 1971; Wilson, 1968). These methods are often used when flow conditions for making current meter measurements or volumetric calibrations are unfavorable such as closed conduits, ice covered reaches, and turbulent mountain streams. The general procedure for dilution measurement is illustrated in Figure 40.

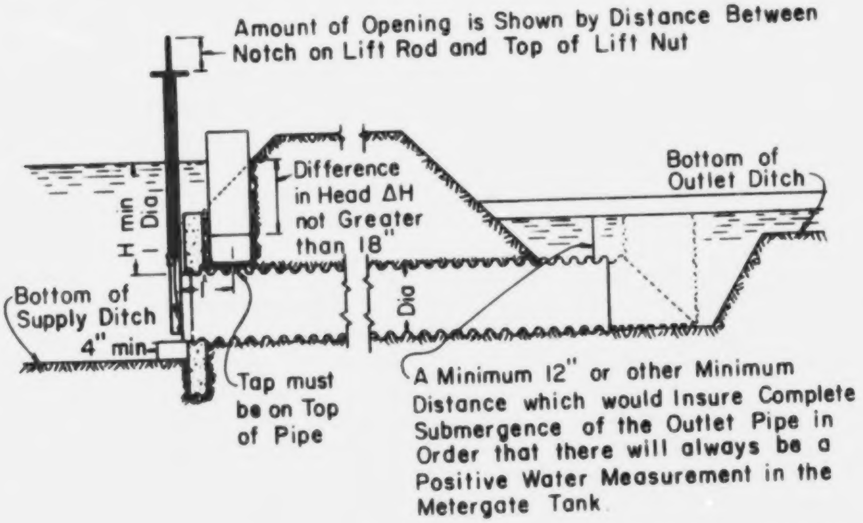
Radioisotope methods are a variation of the dilution techniques that use a radioactive substance as a tracer material. The degree of dilution is indirectly obtained by comparing gamma ray emissions from the concentrated isotope solution and the diluted solution. Geiger counters or scintillation counters are required for this purpose.

One type of acoustic or sonic flow meter operates on the principle that difference in the time of arrival of two simultaneously created ground pulses traveling in opposite directions through the water can be related to the velocity of flow (United States Bureau of Reclamation, 1974). The two sources are placed on opposite sides of the channel, but one is placed a sufficient distance downstream to yield meaningful time differences. Another type of sonic meter is used to measure the stage height by measuring the distance to the water surface from the meter.

Magnetic flow meters utilize a section of nonmagnetic closed conduit with two magnetic coils on opposite sides. In effect, water acts as a rotor in a generator and the induced voltage measured by electrodes in the wall indicates the rate of water flow. Troskolanski (1960) discusses this method in more detail.


Meter Totalizer or
Transmitter for
Remote Recorder
Mounting
Brackets
Propeller
Minimum
Water Surface
Flow
from
Canal
Longitudinal Section
Drop
Pipe
Concrete
Headwall
End View

a) Propeller meter installation for measuring headgate diversions.


Amount of Opening is Shown by Distance Between
Notch on Lift Rod and Top of Lift Nut
Difference
in Head ΔH
not Greater
than 18"
Bottom of
Outlet Ditch
H min
Dia
Dia
Bottom of
Supply Ditch
4" min
Tap must
be on Top
of Pipe
A Minimum 12" or other Minimum
Distance which would Insure Complete
Submergence of the Outlet Pipe in
Order that there will always be a
Positive Water Measurement in the
Metergate Tank

b) Metergate installation for measuring headgate diversions.

Figure 39. Two closed-to-open conduit methods for measuring headgate diversions.

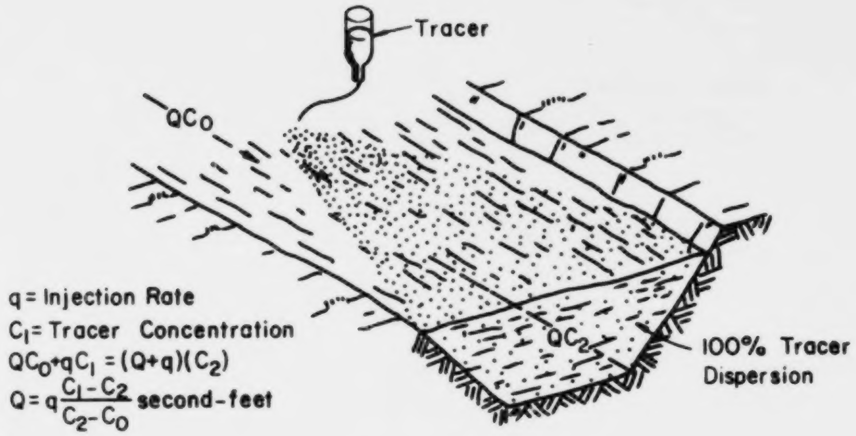

Tracer
QC_0
q = Injection Rate
C_1 = Tracer Concentration
$QC_0 + qC_1 = (Q+q)(C_2)$
$Q = q\frac{C_1 - C_2}{C_2 - C_0}$ second-feet
QC_2
100% Tracer Dispersion

Figure 40. Schematic representation of methodology for chemical dilution techniques of flow measurement (United States Bureau of Reclamation, 1974).

Methods of Measuring Seepage Rates

There have been numerous methods developed for measuring seepage from canals and laterals involving both field and laboratory investigations. Each has its own unique characteristics that make it useful under certain conditions. The objective of this discussion is not to describe different methods of measuring seepage rates, but to provide a review of several methods that could be used as a part of salinity investigations.

The factors influencing seepage rates are many and complex. Among the more important ones are soil characteristics of the channel bed, time of year the tests are made, length of time the channel has been operating, depth to groundwater, sediment load in the water, depth of water in the channel, temperature of both the water and soil, barometric pressure, biological factors and salts contained in both the water and soil (Robinson and Rohwer, 1959; United States Department of Interior, United States Bureau of Reclamation, 1952; United States Department of Interior, United States Bureau of Reclamation, 1963; Rohwer and Stout, 1948; Brockway and Worstell, 1968). Although the literature contains much information about the relationship between these parameters and seepage rates, the seepage process is so complex that individual field tests are required. Worstell (1976) provides an excellent review of seepage measurement techniques.

The most common methods of measuring seepage can be categorized as those that yield results indicating an average seepage from a length of channel and those in which information simply gives the permeability of a sample of the channel bed. If the latter type of measurement is employed, additional information on hydraulic gradients is necessary in order for the actual seepage to be computed. In most salinity investigations, those methods that indicate actual seepage rates prove to be most valuable. Three of the most employed methods include the inflow-outflow method, ponding method, and seepage-meter method.

Inflow-Outflow Measurements--

When the seepage rates from relatively long lengths are to be measured, the inflow-outflow method is a reliable and commonly used technique. The method consists of measuring the inflow and outflow to the canal or lateral section under investigation. It includes all diversions from the channel and return flows to the channel. By computing the net discharge loss in the channel, the actual seepage rate can be determined. Since the usual units of seepage rate are feet per day ($ft^3/ft^2/day$), the conversion from the total loss in the section requires a knowledge of the length and wetted perimeter (average) of the channel. The seepage rate can thus be expressed as:

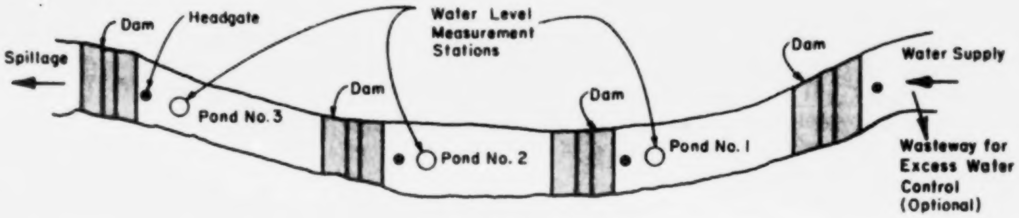
$$SR = \frac{(\text{Inflow} - \text{Outflow}) \times 8.64 \times 10^4}{A} \tag{14}$$

in which SR is the seepage rate in ft/day (average for canal section), 8.64 x 10^4 is the number of seconds per day, A is the average wetted area of the channel in square feet, and the difference between the inflow and outflow is expressed in cfs (ft^3/sec). Use of this method is discussed by Bourns (1955). The canal reach must be of sufficient length so that the seepage loss is much greater than the measurement error or the measured seepage is meaningless.

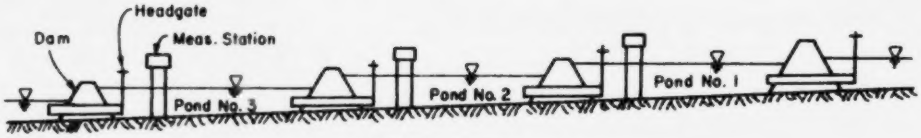
Although this method does give an indication of seepage rates under actual operating conditions, there are several factors that should be carefully observed or large errors will be introduced into the results. The maintenance of constant flow depths in the canal during the tests is essential to eliminate the effects of bank and channel storage. Also, an accounting of all return flows from high lands and diversions or leaks from the canal must be made. Occasionally, if the seepage rates are small, it may be useful to note rainfalls and evaporation, although these latter factors are generally inconsequential. Finally, but probably most important, is the consideration of flow measuring devices to be employed. In the absence of measuring structures in the system, flows generally can be measured by small flumes or weirs when small, and by current water within at least 5 percent if operated correctly. Current meter measurements require careful attention by experienced personnel to maintain accuracies below 5 percent.

Ponding Method--

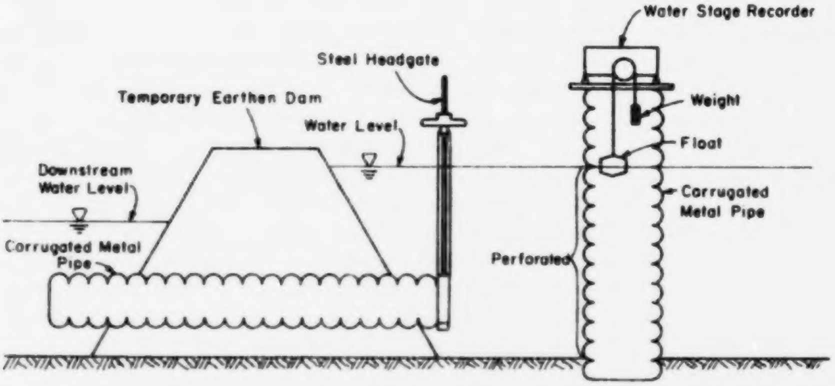
Although an objection is often raised that still water may seep at a different rate than flowing water, the difference is probably small in comparison to errors associated with other measurement methods regarding seepage. Basically, the ponding method involves measuring the rate of fall of the water surface in the pool created in the canal section (Figure 41). Then,


Dam
Headgate
Water Level
Measurement
Stations
Dam
Water Supply
Spillage
Pond No. 3
Dam
Dam
Pond No. 2
Pond No. 1
Wasteway for
Excess Water
Control
(Optional)

Plan View


Headgate
Dam
Meas. Station
Pond No. 3
Pond No. 2
Pond No. 1

Section View
(Not to Scale)


Water Stage Recorder
Steel Headgate
Temporary Earthen Dam
Weight
Water Level
Float
Downstream
Water Level
Corrugated
Metal Pipe
Corrugated Metal
Pipe
Perforated

Temporary Dam and Water Measurement Station Detail

Figure 41. Schematic representation of the ponding test method for seepage measurement.

by knowing the geometric properties of the section which is illustrated in Figure 42, it is possible to compute the seepage rate according to the following formula:

$$SR = \frac{\Delta E \times SW_a \times 24}{WP_a \times T} \tag{15}$$

where ΔE is the drop in water surface elevation in feet, SW_a is the average surface width in feet, WP_a is the average wetted perimeter in feet, and T is the time of the run in hours. Some of the details and layout considerations for ponding tests are shown in Figure 41. Further information on the analysis can be found in Skogerboe and Walker (1972).

The ponding method usually provides the basis for comparison with other methods because it can be expected to yield the best results (Robinson and Rohwer, 1959; United States Department of Interior, United States Bureau of Reclamation, 1968). It does have certain disadvantages that should be delineated. Construction of the dikes is often expensive and must be completed during periods when the canal is not in use, or during periods of interrupted canal operation. Providing water to fill the pools or ponds may represent a significant problem. If the canal discharges are very large in relation to the seepage rates, then the ponding method is the best method by which the seepage rates can be determined. Under such conditions, errors expected in other methods, such as the inflow-outflow method, may not be able to discern any seepage loss. Table 10 presents an example of the calculations involved in ponding method tests.

Seepage Meters--

Seepage meters determine seepage rates under normal operating conditions, but only for a small area at a time. Nevertheless, by taking readings at several points along the canal section, a realistic average value can be determined. One type of seepage meter uses a cylindrical bell that is pressed into the channel bed. Attached to the bell via plastic hose is a plastic bag filled with water that is submerged in the channel. Water that seeps into the channel bed is replaced by water in the bag which is under the same pressure as the channel flows. Seepage from the bell is determined by weighing the plastic bag before and after the test, and the elapsed time of the test. The seepage rate then may be determined by:

$$SR = \frac{Q}{A \times T} \tag{16}$$

in which Q is the amount of water that seeped through the canal bank in ft^3, A is the area of the bell in ft^2, and T is the elapsed time in days.

TABLE 10. TABLE FOR COMPUTING SEEPAGE LOSSES (USBR, 1968)

1	2	3	4	5	6	7	8	9	10	11	12
Date	Time	Elapsed time, hours	Water surface elevation	Drop in water surface feet	Water surface width feet	Average water surface width feet	Product of Columns 5 & 7	Wetted perimeter, feet	Average wetted perimeter	Product of Columns 3 & 10	Seepage rate cfd $\frac{\text{Col. 8} \times 24}{\text{Col. 11}}$
9/16	9:00AM		1910.70		13.8			15.9			
		6.0		.18		13.55	2.44		15.55	93.4	0.63
9/16	3:00PM		1910.52		13.3			15.2			
		8.0		.28		12.85	3.60		14.55	116.4	0.74
9/16	11:00PM		1910.24		12.4			13.9			
		10.0		.35		11.45	4.01		13.15	131.5	0.73
9/17	9:00AM		1909.89		10.5			12.4			
		8.0		.25		10.3	2.60		12.1	96.8	0.65
9/17	5:00PM		1909.64		10.1			11.8			
		8.0		.21		9.9	2.08		11.65	93.2	0.54
9/18	1:00AM		1909.43		9.7			11.5			
		-REFILL									
9/18	9:00AM		1910.42		12.8			14.4			
		3.0		0.10		12.7	1.27		14.2	42.6	0.72[1/]
9/18	12N		1910.32		12.6			14.0			
		5.0		0.16		11.75	1.88		13.85	69.3	0.65
9/18	5:00PM		1910.16		11.9			13.7			

BASIC EQUATION:

$$(\text{cfd}) = \frac{\text{Length of Pond} \times \text{Drop in Water Surface} \times \text{Average Width of Water Surface} \times 24}{\text{Length of Pond} \times \text{Average Wetted Perimeter} \times \text{Hours of Run}}$$

[1/] Note that an error of 0.01 in gage readings in this calculation would influence the seepage rate 10%. The time interval is too short.

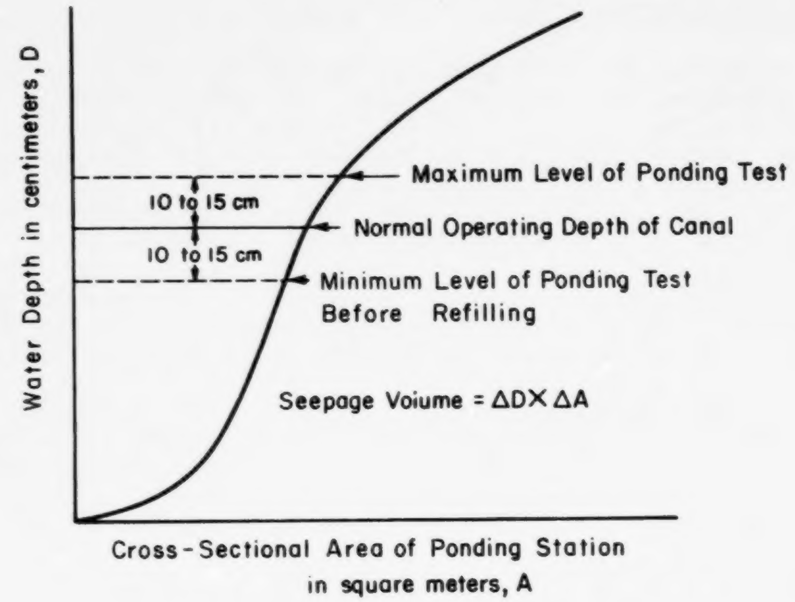


Figure 42. Typical relationship of water depth and area which need to be determined for seepage tests.

The seepage meter may be expected to work well unless the bed material is badly disturbed during meter installation causing the meter to over estimate seepage rates. The seepage meter method is difficult to apply under conditions in which the flow depths are too great or the channel velocities are too fast. Gravel, moss, or heavily vegetated channels present difficulties in properly evaluating seepage rates.

There are numerous other techniques that yield useful seepage rate results in certain conditions. The first group of these may be classified as measurements of soil permeabilities that can be used to compute seepage rates. These include the well-permeameter method, variable head permeameter method, and the laboratory permeameter method (Robinson and Rohwer, 1959). The second group are those that use trace materials to determine seepage loss. These include the salt-penetration technique, the radioactive isotopes technique, and fluorescent dyes (Liang and Richardson, 1971; and Robinson and Rohwer, 1959).

FARM SUBSYSTEM INVESTIGATIONS

Farm investigations for nonpoint pollution control constitute the largest proportion of work involved in the evaluation of an irrigated area. The primary component of this investigation is the farm efficiency studies which include evapotranspiration, infiltration, tailwater, irrigation method analysis, and vegetative land use mapping.

Farm Efficiency Studies

The amount of water diverted is also very critical in establishing the water-salt budgets for a farm or a field. All of this water must be measured and accounted for, and it is allocated to any one of three main categories. The surface hydrology categories are (a) evapotranspiration, (b) infiltration and (c) tailwater runoff (Figure 43). In areas with a high water table, there can be a substantial amount of water that moves upward via capillary action from the water table and is used by the plants. This capillary water will usually contribute significantly to soil salination problems. The subsurface hydrology categories are head ditch seepage and deep percolation losses. The variables that must be considered in an on-farm irrigation return flow investigation are schematically illustrated in Figure 44.

Many of the parameters such as drainage discharges, lateral diversions, water quality, and precipitation can be measured directly. Others must be investigated indirectly. These indirect measurements of parameters are related mostly to groundwater movement and soil hydraulic characteristics and can be monitored using techniques such as piezometers, wells, and soil sample analyses.

Because so many of the parameters in the water and salt budgets cannot be evaluated directly on a large scale, peripheral investigations are usually made in which a portion of the area is examined in detail. Such investigations include farm efficiency studies that indicate the relative proportion of evapotranspiration, deep percolation, and soil moisture storage; vegetative land use mapping of the entire irrigated area so that the total consumption of water for the area can be calculated; and other studies pertaining to specific conditions of water and salt movement. There is no substitute for good field data collection. The United States Geological Survey (1968 to 1976) has published 34 manuals on techniques used for water resource data collection, many of which are very useful for irrigation return flow studies.

Basic Data

Four types of basic data are required for on-farm water use investigations. These are crop parameters, soil parameters, water quality information, and climatic data, such as evapotranspiration and precipitation data.

Crop parameters are important to many of the irrigation method decisions and the plant sensitivity and ionic toxicity response to salinity, growth rates, and evapotranspiration demands. Crop responses to salinity are discussed by Bernstein and Hayward (1957), Bernstein et al. (1954), Black (1968), Maas and Hoffman (1977), Robinson (1971), and others. Climatic data requirements, evapotranspiration and growth rates are reviewed later in this section.

Soil parameters considered as basic data include field capacity, permanent wilting point, and bulk density for each soil layer with depth. Since field soil-moisture sampling procedures are gravimetric, the bulk density is needed to relate gravimetric to volumetric moisture content which is

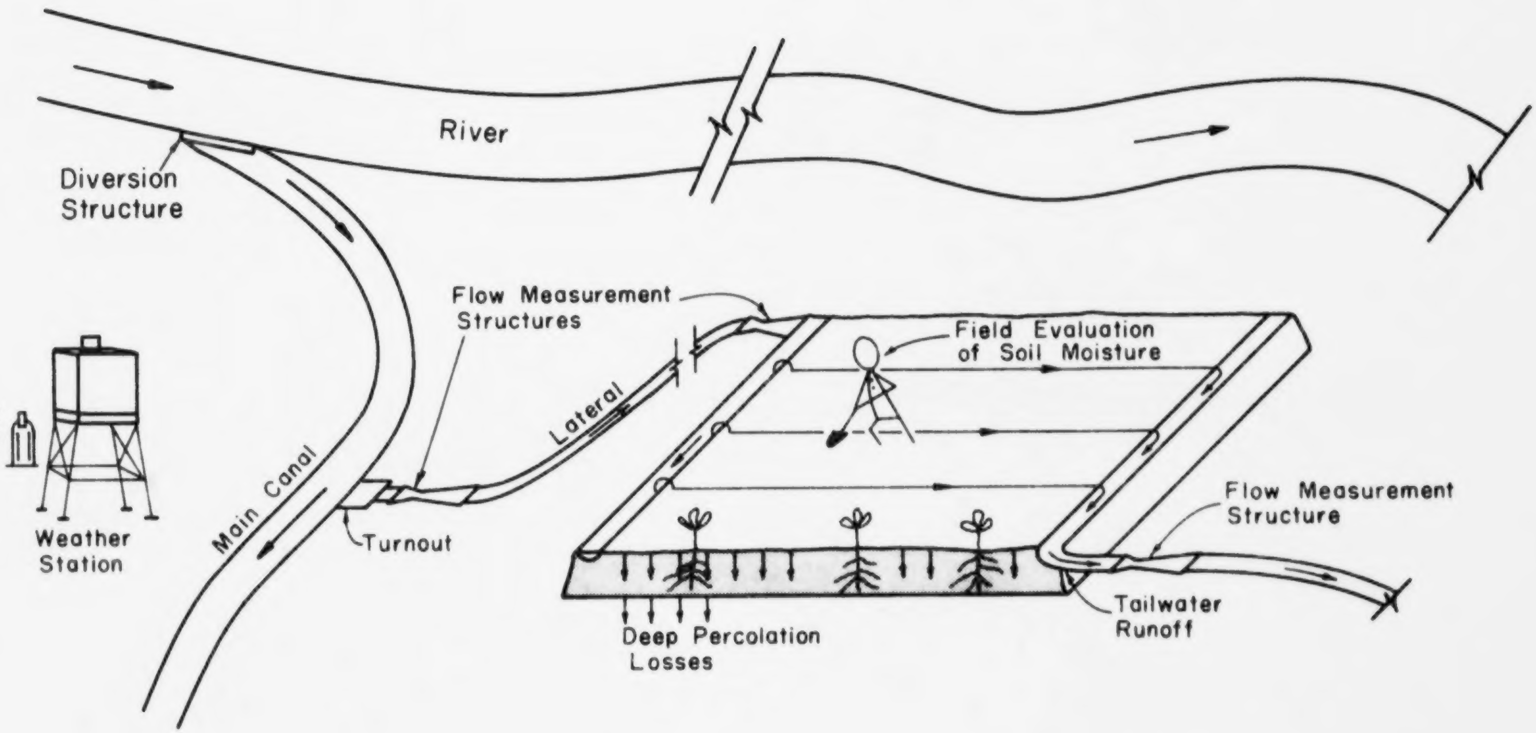

River
Diversion
Structure
Main Canal
Turnout
Flow Measurement
Structures
Lateral
Field Evaluation
of Soil Moisture
Flow Measurement
Structure
Tailwater
Runoff
Deep Percolation
Losses
Weather
Station

Figure 43. Schematic of instrumentation required for on-farm hydrology investigations.

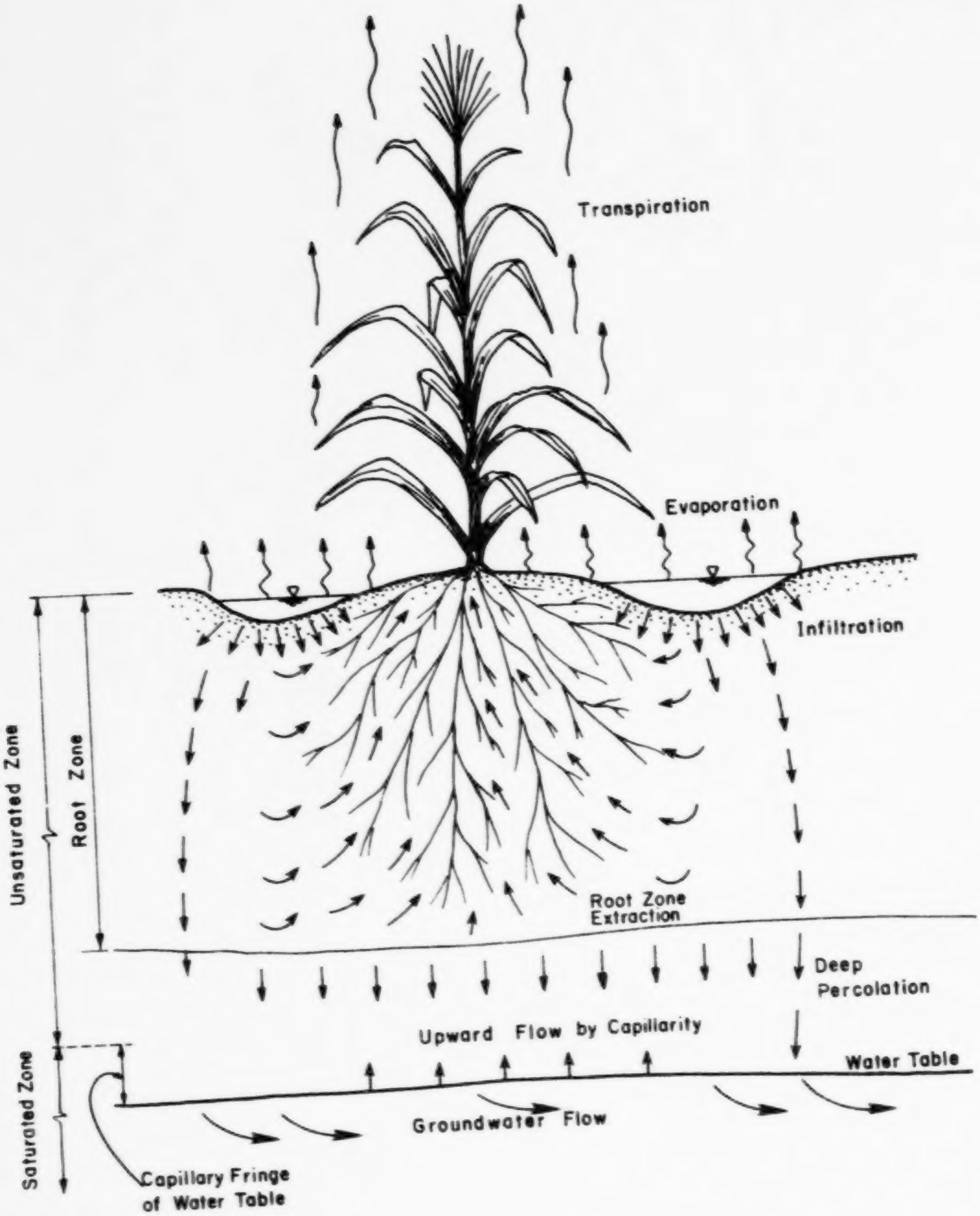

Transpiration
Evaporation
Infiltration
Unsaturated Zone
Root Zone
Root Zone Extraction
Deep Percolation
Upward Flow by Capillarity
Water Table
Saturated Zone
Groundwater Flow
Capillary Fringe of Water Table

Figure 44. Schematic of the hydrologic variables to be considered in an on-farm subsystem investigation.

used in most analytical procedures. An attempt should be made to obtain several samples from numerous locations to approximate the average conditions of the field (Warrick, 1977; Karmeli et al., 1978). Basic soil chemistry reactions, electrical conductivity and ionic content of the soil solution should also be determined. Black et al. (1965), Food and Agricultural Organization of the United Nations (1975), Quirk (1971), Richards (1954), United States Department of Agriculture (1964a), Bolt and Bruggenwert (1976), Chapman (1966), and others describe the soil-chemistry-plant relationships and procedures for data collection and analysis.

Quality of the incoming water can greatly influence management and operation of an irrigation system. If the water is of poor quality, it can limit many of the alternatives for pollution control. Ayers (1976), Ayers and Westcot (1976), Christiansen et al. (1976), Kemp (1971), Kovda et al. (1973), Wilcox and Durum (1967) and others present information regarding water quality in irrigated agriculture.

Evapotranspiration--

A review of the alternative approaches to estimating the volume and rates of water evaporated from wet crop and soil surfaces or transpired by the plants can be found in several sources (Jensen, 1973; Doorenbos and Pruitt, 1977; Horton, 1973). As far as this technology is applicable to the management of irrigation return flow quality through irrigation scheduling, Skogerboe et al. (1974a), Jensen (1975, 1976) provide good summaries.

There are many methods by which evapotranspiration (ET) can be calculated. The three most common approaches to estimating evapotranspiration are: (a) the Blaney-Criddle method (United States Department of Agriculture, Soil Conservation Service, 1964b); (b) the Modified Jensen-Haise methods; and (c) the Penman Combination method. These methods represent the range of sophisticated techniques available today, varying in detail from a temperature dependent analysis (Blaney-Criddle) to an analysis of energy balance and convective transport (Penman).

Depending on the estimating formula used, data required for consumptive use studies can include climatic data such as daily solar radiation, air temperature, dew point temperature, relative humidity, wind speed, and precipitation. Some consumptive use formulas require information on the monthly percentages of daylight hours, latitude, altitude, crop height, depth of root zone, crop and phreatophyte growth stage coefficients, and the areal percentage of plant cover.

Evapotranspiration is a very important part of any water-salt budget since it can account for the majority of the water delivered to an irrigated area. The accuracy of these measurements and resulting calculations can seriously affect the validity of the results. It is necessary that this value be determined as accurately as possible, and it is imperative that the method of estimating evapotranspiration be calibrated for local conditions. Attempts to base conclusions on uncalibrated consumptive use equations would be extremely presumptuous. These equations are usually calibrated by the use of field measurements. A detailed discussion of the calibration procedure and comparisons of the three main estimating formulas mentioned above can be found in Evans et al. (1978b).

It is usually necessary to apply the results of the study area to the entire area, which includes extending the water-salt budgets. A very important part of consumptive use studies is vegetative mapping of the areal extent of each crop. This should be done each year in the study area, and at least once for the entire irrigated area. Since each crop uses varying amounts of water at different times, it is advantageous to know the acreages, planting and harvesting dates, as well as the dates of irrigation. Most of the data available from the Agricultural Stabilization and Conservation Service or the Census of Agriculture do not have sufficient resolution to be used for hydro-salinity investigations. It is often necessary for project personnel to map the agricultural land use of these areas.

Measurement of Evapotranspiration--Tanner (1967) and the World Meteorological Organization (1966) provide an excellent review of the procedures and methodologies used for the measurement of potential evapotranspiration in the field. Measurement of evapotranspiration should include the means for the actual measurement of consumptive use and a complete weather station to measure air temperature (including maximum and minimum daily temperatures), dew point temperature, relative humidity, precipitation, wind run, solar and net radiation, and evaporation (Class A pan). Doorenbos (1976) presents an excellent discussion on the establishment and operation of a weather station and the calibration of empirical evapotranspiration indices to actual evapotranspiration measurements. The World Meteorological Organization in 1970 and 1971 presented much information on the collection and analyses of hydrometeorological data.

Probably the most accurate measurement of evapotranspiration is obtained by the use of lysimeters. A lysimeter is a device that is hydrologically isolated from the surrounding soil. This device contains a known volume of soil, is usually planted to the crop under study, and has some means to directly measure the consumptive use of water. Lysimeters must be representative of the surrounding conditions and the soil types if they are to provide useful evapotranspiration measurements. Lysimetry establishes a datum for evapotranspiration calculations because it is the only method of measuring evapotranspiration where the investigator has complete knowledge of all the terms of the water balance equation. Harrold (1966) presents a comprehensive review of the use of lysimeters for measuring evapotranspiration.

Two types of lysimeters, which have worked quite well for calibration purposes, are the constant water table and the hydraulic weighing lysimeters. The constant water table lysimeters are usually planted to grass, such as Kentucky Bluegrass or other crops with shallow root systems. On the other hand, the hydraulic weighing lysimeters are usually planted to deeper rooted crops, such as alfalfa or corn.

Construction of a constant water table lysimeter is shown in Figure 45. They are usually about 1 meter square and about 40 to 60 cm deep. The amount of water used is calculated by using an area ratio of the lysimeter to the reservoir. The evapotranspiration rate is very sensitive to the depth of the water table in the lysimeter which is usually kept at about 15 cm below the grass surface. The crop must be trimmed periodically to ensure

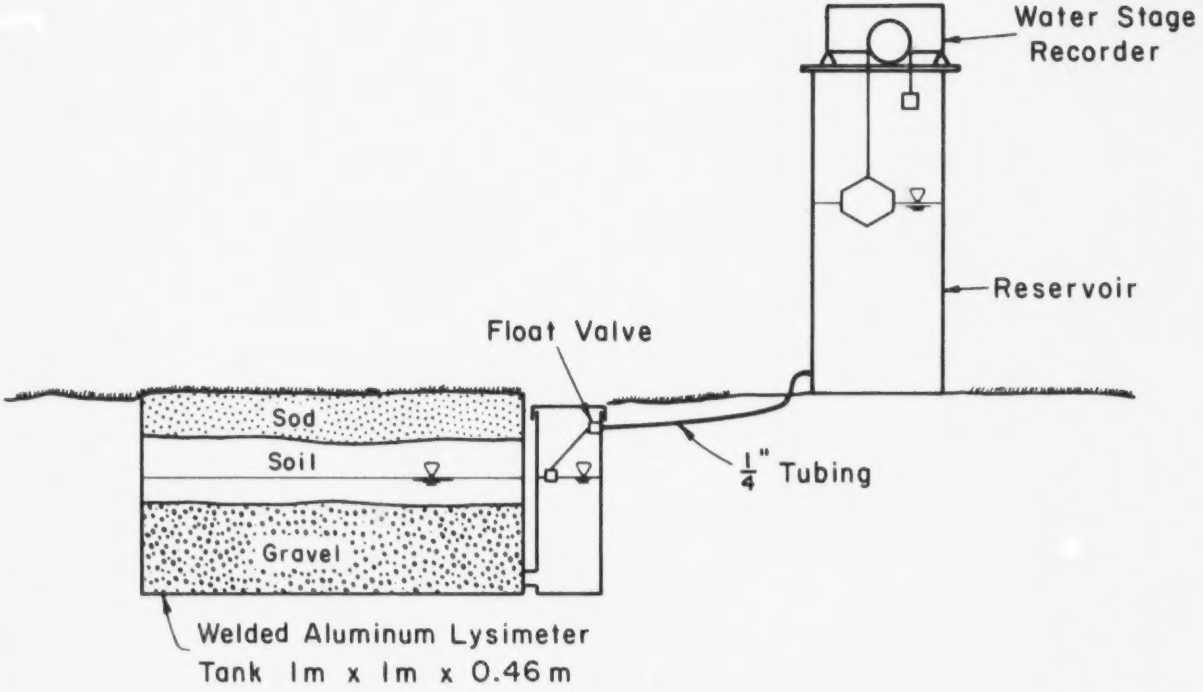

Water Stage
Recorder
Reservoir
Float Valve
Sod
Soil
Gravel
$\frac{1}{4}$" Tubing
Welded Aluminum Lysimeter
Tank 1m x 1m x 0.46 m

Figure 45. Schematic of constant water-table lysimeter.

vigorous growth; and any vegetative growth extending over the sides of the lysimeter should be trimmed back. Construction of one of these types of lysimeters costs from $250-300 each, not including the water level recorder.

Construction of a hydraulic weighing lysimeter is shown in Figure 46, and a typical calibration curve is shown in Figure 47. This type of lysimeter is irrigated for the purpose of maintaining low-tension soil moisture conditions in order to approximate the potential evapotranspiration. A neutron probe access tube or other method can be installed to assist in monitoring soil moisture distribution. A method to extract the surplus water and to provide a leaching mechanism should be installed. One bar ceramic candles connected to a vacuum system work well for this purpose. Depending on the degree of sophistication, this type of lysimeter can cost from $1,000-3,000 each to construct (Hanks and Shawcroft, 1965).

Land Use Mapping--

Significant agricultural land use surveys have been conducted by the United States Department of Agriculture, Soil Conservation Service for many irrigated areas in the United States. Detailed soil survey information has been developed for almost all irrigated areas.

The type of land use data required for the preparation of a water budget consists of delineating the various types of vegetation and land requirements that utilize water in excess of normal precipitation. This cataloging process is an expensive and time-consuming effort that includes separating the agricultural areas from the wetland phreatophytes, the urban areas and the industrial areas, as well as the open water surfaces. These types of studies are not only necessary for budgeting procedures, but they also provide an excellent data base for future studies in an area for many disciplines. These data must be collected by field investigations.

Aerial photographs are an excellent resource for vegetative land use mapping. The most current photographs available should be used since land use changes are usually minimal, field boundaries and ditches remain the same, farmsteads and urban areas are well defined, and adjustments and updating are easily accomplished.

Aerial photographs with almost any scale are available for most areas in the western United States and can be ordered from the United States Department of Agriculture, Agricultural Stabilization and Conservation Service, Aerial Photography Division, Western Laboratory in Salt Lake City, Utah. It is important to select a scale for the photographs that corresponds to other base maps or design maps that exist or will be used for the project.

The range, township, and section numbers are marked on the photographs that are then taken into the field. The existing land use is marked on the appropriate photographs for each field. A suggested land use mapping index is presented in Table 11. Other indices are used by the United States Bureau of Reclamation, the Soil Conservation Service, and other agencies. Whatever index is used for mapping purposes, it should be compatible with other studies undertaken in the area or river basin. A typical photograph from which the land uses were labeled in accordance with the water related land

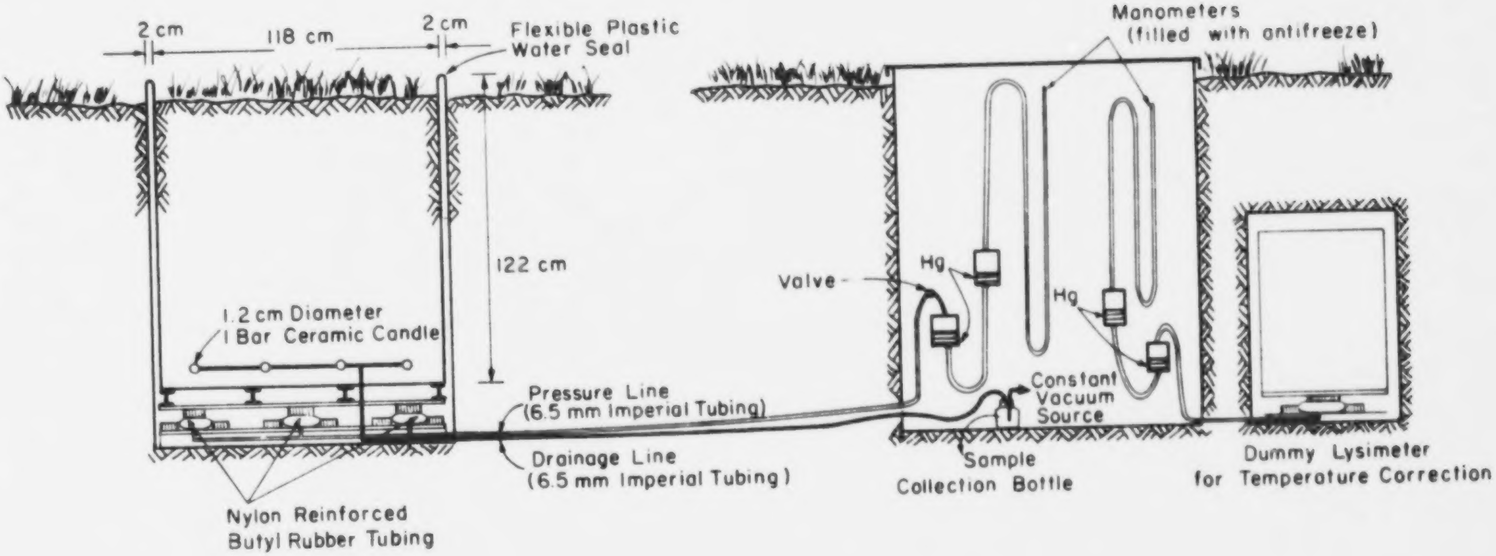

2 cm
118 cm
2 cm
Flexible Plastic Water Seal
122 cm
1.2 cm Diameter 1 Bar Ceramic Candle
Nylon Reinforced Butyl Rubber Tubing
Pressure Line (6.5 mm Imperial Tubing)
Drainage Line (6.5 mm Imperial Tubing)
Valve
Hg
Hg
Manometers (filled with antifreeze)
Constant Vacuum Source
Sample Collection Bottle
Dummy Lysimeter for Temperature Correction

Figure 46. Schematic of the construction of a hydraulic weighing lysimeter.

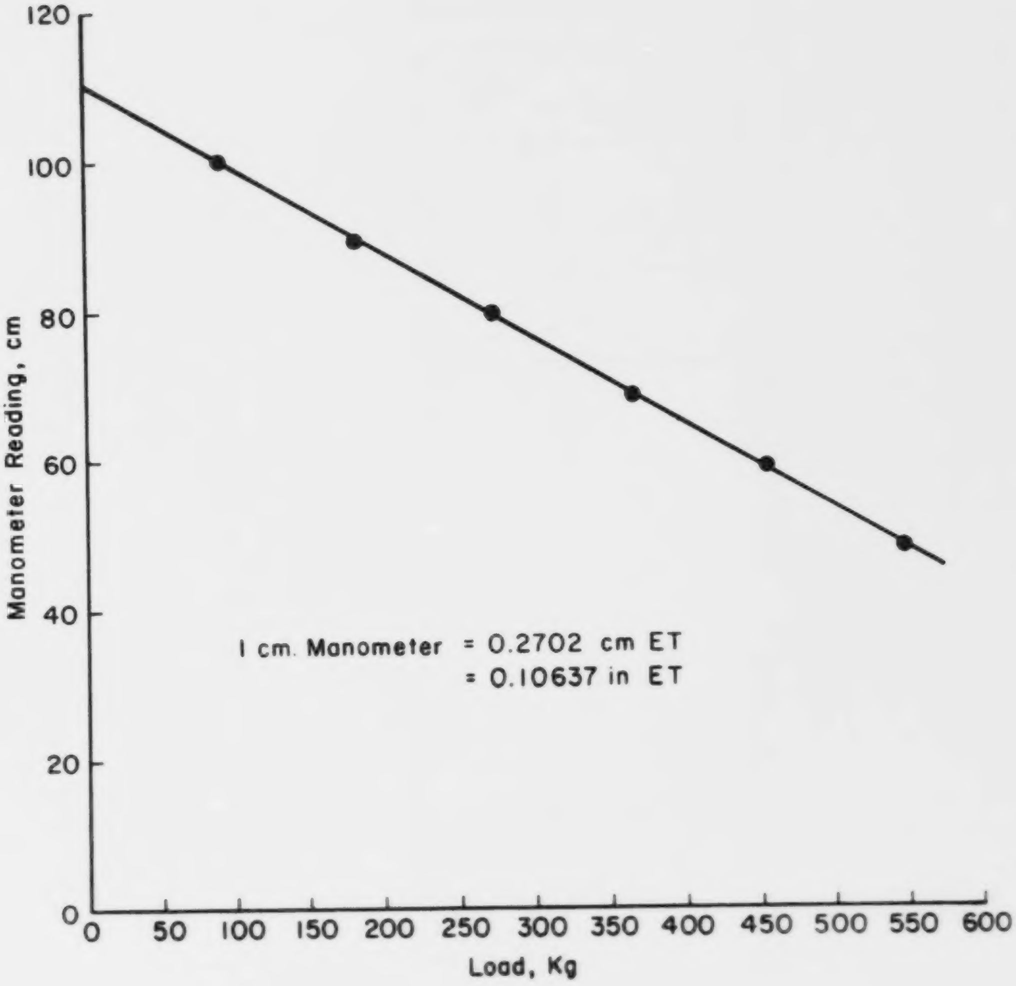


Figure 47. Typical calibration curve for hydraulic weighing lysimeter.

TABLE 11. SUGGESTED LAND USE MAPPING INDEX

A. Irrigated Cropland
  1. Corn
  2. Sugar beets
  3. Potatoes
  4. Peas
  5. Tomatoes
  6. Truck crop
  7. Barley
  8. Oats
  9. Wheat
  10. Alfalfa
  11. Native grass hay
  12. Cultivated grass and hay
  13. Pasture
  14. Wetland pasture
  15. Native grass pasture
  16. Orchard
  17. Idle
  18. Other

B. Dry Cropland
  1. Alfalfa
  2. Wheat
  3. Barley
  4. Beans
  5. Cultivated grasses
  6. Fallow
  7. Other

C. Other Land Use
  1. Farmsteads
  2. Residential yards
  3. Urban
  4. Stock yards
  5. School yards

D. Industrial
  1. Power Plants
  2. Refineries
  3. Meat Packing
  4. Other

E. Open Water Surfaces
  1. Major storage
  2. Holding storage
  3. Sump ponds
  4. Natural ponds

F. Phreatophytes
  1. Cottonwood
  2. Salt Cedar
  3. Willows
  4. Rushes or Cattails
  5. Greasewood
  6. Sagebrush and/or rabbitbrush
  7. Wildrose, Squawberry, etc.
  8. Grasses and/or Sedges
  9. Atriplex

P. Precipitation only

use index is shown in Figure 48. For example, a field marked A1 on the aerial photograph indicates that during that year, corn was grown in that field. Although it is realized that certain changes occur from year to year, it is usually safe to assume that the total acreages and the general distribution of crop acreages over a large area varies slowly with time.

Due to scale distortion, which is always present in aerial photographs, an effort should be made to prepare land use base maps with accurately placed section lines. To assist in accomplishing this, maps should be prepared using a grid based on geodetic coordinates. This is usually not a problem since most agricultural areas in the western United States have roads and field boundaries corresponding to these coordinates. The scale of the base maps should correspond directly to the scale of the aerial photographs. United States Geological Survey quadrangle maps can be used for control where available. In addition, there are several computer techniques that correct for distortion if adequate ground control is established.

Results of these investigations, including the base maps and tabulation of the data for each section or subgroup, would be organized and made available for public distribution. This type of information is very valuable and is needed by many state and local planning agencies, public interest groups, environmental impact assessments, and for other groups and purposes. This information also provides a good basis for comparison of future land use related investigations. Examples of these types of examinations can be found in Walker and Skogerboe (1971) and Evans et al. (1973).

The various water related land use areas are then transferred from the aerial photographs to the base maps which also depict the individual field boundaries (Figure 49). The irrigation conveyance system should be added to the base maps in order that lands served by each canal or lateral can be established.

Many sections are not exactly 640 acres (259 ha), and they can often vary by as much as ± 10 percent of this value (as much as 90% on correction lines). It is necessary, therefore, to establish the area of each section. One method is to use graphical computer techniques or a planimeter on each section from the quadrangles to arrive at the acreage for that section. Another method is to check the land survey maps in the local County Recorder's office. The acreage of each land use within that section must also be determined from the base maps by similar methods. The acreage of each land use is then summed for each canal, lateral, or watershed in order to develop the necessary water budgets.

Infiltration--

Infiltration, which refers to the rate at which water will move into the soil profile, is a very important and necessary component of the farm subsystem evaluation. Information on infiltration is necessary to predict the maximum application rates, the quantity of water to be delivered, and the effect of modifying deep percolation losses. Irrigations cannot be effectively scheduled unless the temporal and spatial distribution of water is known. Infiltration characteristics should be determined at numerous locations in a field.

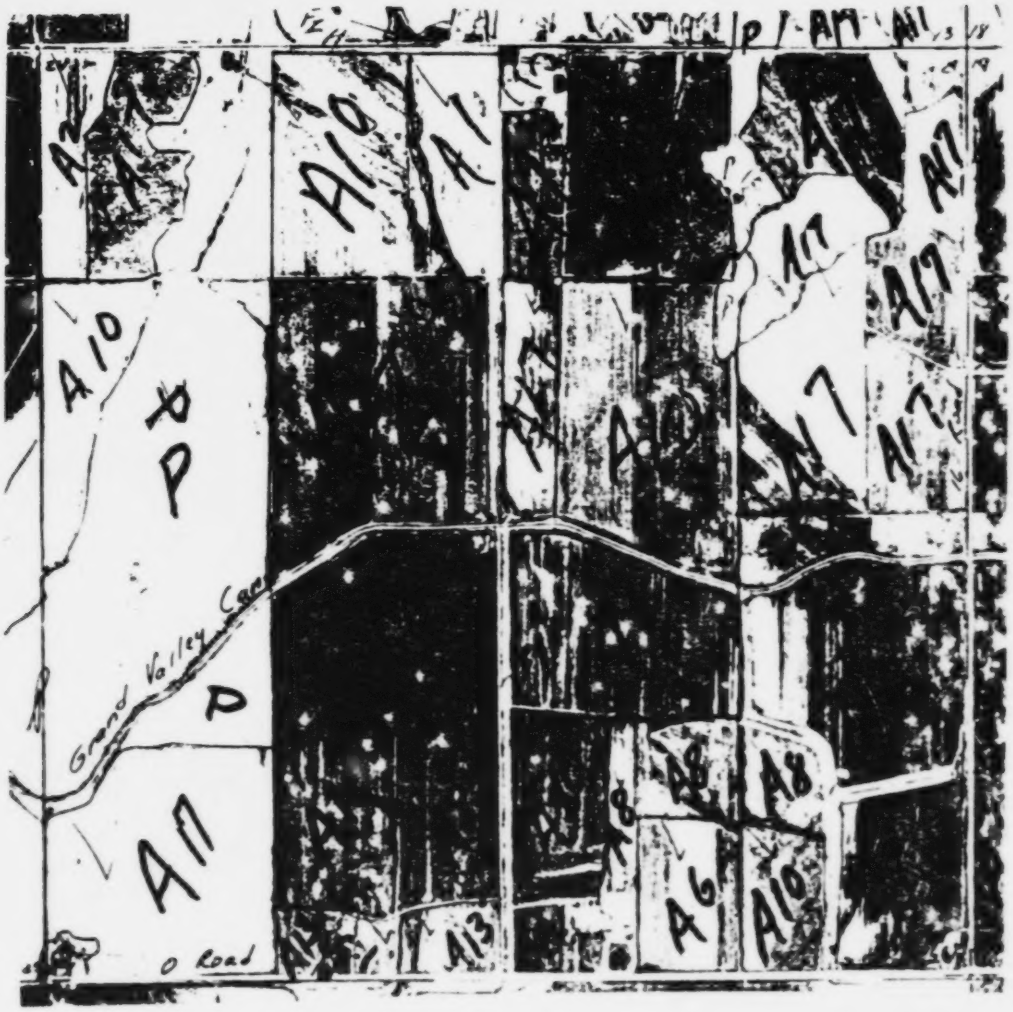

A10
A17
A17
A17
A10
P
P
A10
A17
A17
Grand Valley Can
P
A17
A8
A8
A8
A6
A10
A13
O Road

Figure 48. Typical areal photograph used for land use mapping showing the land use mapping index used in Table 11.

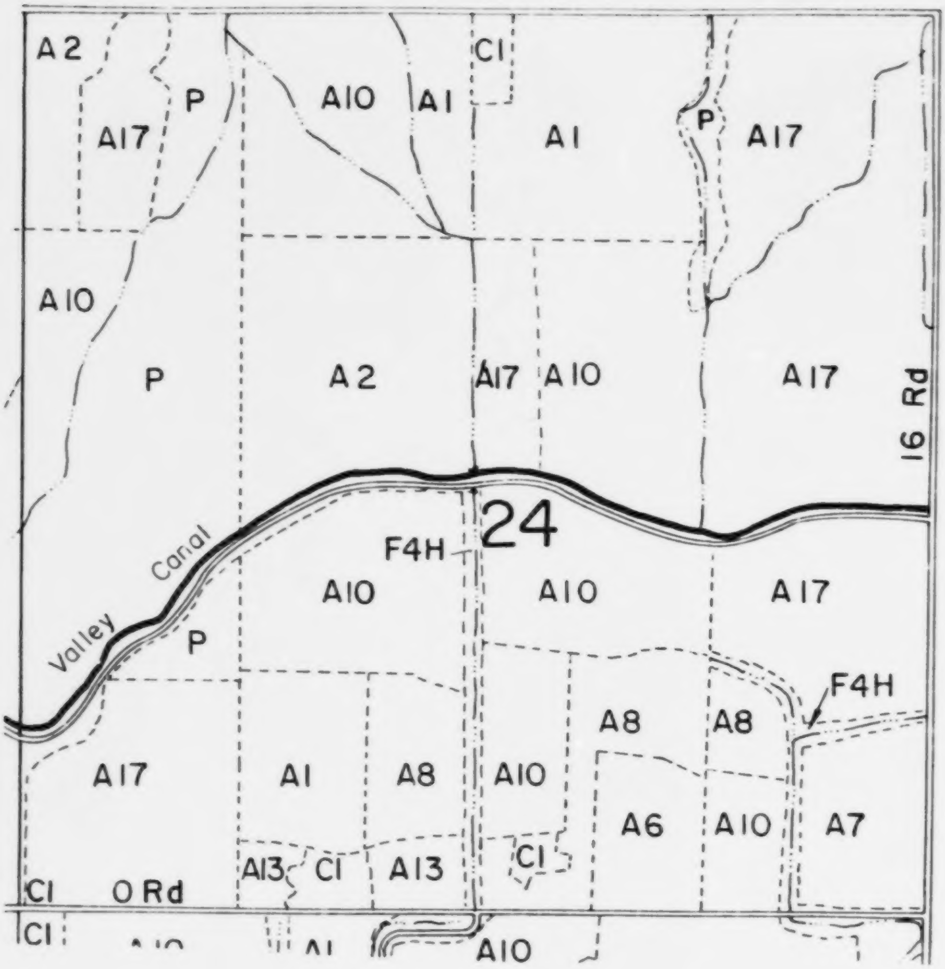

A2
A17
P
A10
A1
C1
A1
P
A17
A10
P
A2
A17
A10
A17
16 Rd
24
F4H
Valley Canal
A10
A10
A17
P
F4H
A8
A8
A17
A1
A8
A10
A6
A10
A7
C1
A13
C1
A13
C1
O Rd
C1
A1
A10

Figure 49. Finished map corresponding to the areal photograph shown in Figure 48.

Infiltration rates vary throughout the irrigation season as well as from year to year and are due to many factors. In addition, infiltration rates are dependent on soil moisture content and crop type and whether it is annual or perennial. Drainage problems such as perched water tables, restrictive soil layers (plow layers, geologic conditions, mineral depositions such as caliche layers), sodium problems, soil sealing due to compaction and/or soil crusting, and surface roughness and shape can also significantly affect infiltration.

There are several methods for measuring soil infiltration characteristics. The most common is probably the cylinder infiltrometer (Haise et al., 1956; McCulloch, et al., 1967). This method utilizes a steel cylinder or pipe (usually 30-40 cm in diameter) which is forced into the soil to a depth of 10 to 20 cms. The area around the cylinder and the cylinder are filled with water and the change of the depth of water with time is recorded.

Davis and Fry (1963) discuss the measurement of infiltration in furrows. The blocked-furrow infiltrometer (Bondurant, 1957), utilizes two steel plates, usually 1 meter apart, which are forced into the soil along a furrow. The volume of water necessary to maintain the water level between the plates at a specified level, which should approximate normal flow depth in the furrow, will indicate the infiltration rate. Karmeli, et al., (1978) presents an analysis of this type of data. Methods for evaluating border infiltration are presented by Finkel and Nir (1960), Gilley (1968) and others.

Another method of measuring the infiltration characteristics in surface irrigation are the advance-recession tests (Merriam et al., 1973). Methods of analysis of advance-recession infiltration data are discussed by Wilke and Smerdon (1965), Fok et al. (1971), Christiansen et al. (1966), Fok and Bishop (1965), Gerards (1978), Phillip and Farrell (1964), and Karmeli et al. (1978). This procedure uses the rate of water advance and of recession down a furrow or border to indicate the infiltration. The mathematics, however, can become very complicated.

Probably the most common mathematical description of infiltration is the use of the Kostiakov equation (Kostiakov, 1932) which is commonly given as $I = At^B$, with I defined as the total infiltrated depth, t is the time, and A, B are empirical constants. The instantaneous infiltration function follows a decaying exponential function with time and asymptotically approaches a value often referred to as the basic infiltration rate. The basic infiltration rate is often used as the application rate for conservatively designed sprinkler systems.

Tailwater runoff--

In analyzing field tailwater runoff, it is necessary to obtain the runoff hydrograph for each irrigation and for each field. A common error in tailwater investigations is that conclusions are often extrapolated from one or two daily, or even one or two weekly, flow measurements.

Figure 50 shows an actual tailwater hydrograph obtained from a clock-driven water level recorder on a 6-inch Parshall flume. The "valleys" shown in the figure indicate, with a certain time lag, the time the water for each

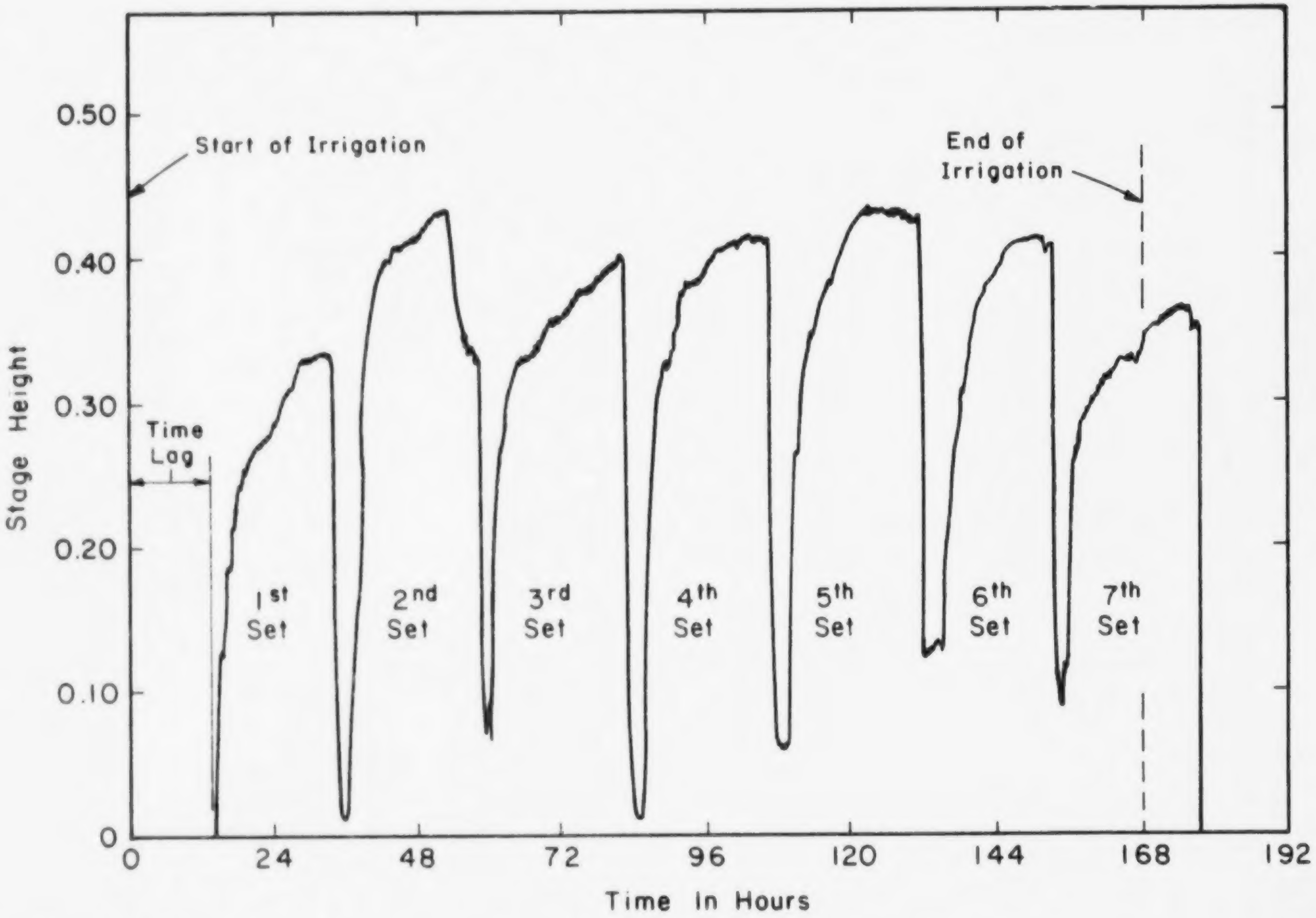


Figure 50. Typical hydrograph of field tailwater for surface irrigation.

individual set was turned off. The time lag is due to the recession phase of irrigation, or the time that it takes for the water to travel the length of the field. The area under the "hills" in Figure 50 is the volume of runoff from each set. The height of the "hills" indicates the maximum rate of runoff during an irrigation set. Therefore, it can be seen that unless continuous hydrographs are obtained, tremendous error could be introduced by "spot" measurements.

Irrigation Method Analysis

Generally, there are four main types of irrigation systems.

1. Surface irrigation systems which include furrow, corrugation, graded borders and basins; (Bishop et al., 1967; Booher, 1974; United States Department of Agriculture, 1974a);
2. Subsurface irrigation (Criddle and Kalisvaart, 1967);
3. Sprinkler irrigation systems (Christiansen, 1942; Davis and Christiansen, 1967; Fry and Gray, 1971; United States Department of Agriculture, 1974b; Pair et al., 1975).
4. Trickle or drip irrigation (Barrs, 1976; Keller and Karmeli, 1975; Rolland, 1972; Geohring, 1976; Jobling, 1974; Shoji, 1977; Smith and Walker, 1975; Wierenga, 1977; Goldberg et al., 1976).

Since subsurface irrigation systems, not including subsurface drip irrigation, are relatively rare, require high quality water, and are not found in areas that significantly contribute to nonpoint pollution, they are not described in this section.

Procedures for evaluation of sprinkler and surface irrigation systems are described by Merriam et al. (1973), Merriam (1968), and Criddle et al. (1956). Further examples of the complete analyses are presented by Evans et al. (1978b), and Karmeli et al. (1978).

Managerial or irrigation policy factors that influence the irrigation are only indirectly dependent on the irrigation method. These decisions include: (a) the irrigation requirement, determination of evapotranspiration needs, soil moisture deficits, and leaching requirements based on water quality; (b) irrigation scheduling decisions regarding the depth of water to be applied and the date of irrigation; and (c) irrigation cost factors that may be constraints to efficient irrigation, such as labor, energy, or capital. Other factors that are managerial decisions include cultural practices, such as planting, fertilization, cultivation, and harvesting operations which can influence timing and depths of applications.

For purposes of analysis, it is necessary to divide the irrigation method evaluation into two categories: (a) application characteristics that are basically functions of operational procedures; and (b) physical operational parameters of the application system that are functions of design, water availability, and soil hydraulic characteristics.

Water Application Characteristics--
There are two subcategories to be determined in the evaluation of water application characteristics. These are the average depth applied, and spatial and depth distribution of water in the field. The latter subcategory is further divided into losses such as field tailwater and deep percolation, and the various efficiency and uniformity parameters necessary to statistically describe the spatial distribution of water.

Various types of irrigation efficiencies are discussed by Bos and Nugteren (1974), Israelsen and Hansen (1967), Karmeli et al. (1978), Jensen (1967), Somehalder (1958), and Willardson and Bishop (1967). The evaluation and description of spatial distribution of water in the field (uniformity) is discussed by Karmeli et al. (1978), Hart (1961), Hart and Reynolds (1965), Karmeli (1977), Seniwengse et al. (1972), and Chaudry (1976, 1978).

Physical Operation Conditions--
Determination of the physical characteristics of the water application system is a relatively straightforward process. For example, the dimensions of pipes or ditches, sprinkler spacing, topographic information such as the field slopes, lengths, widths and areas, the quantity of flow available, pumping lifts and water pressure are all easily measured by conventional means. The application for sprinkler or drip systems can be measured volumetrically by metering devices.

Physical operational conditions or irrigation method factors that influence irrigation are the physical characteristics and constraints of the system such as pipe sizes and lengths, water availability (quantity and timing), pressure, soil infiltration characteristics and physical properties of the field, including acreage, slope, length, and width. Other factors include the water application characteristics of the system which are directly influenced by the management decisions, such as depth actually applied, soil moisture storage capacity, spatial and depth of soil moisture distributions (water losses, uniformities, efficiencies) and the application rate when sprinklers or drip irrigation systems are considered. One of the most critical parameters of the farm efficiency studies is the change in soil moisture storage throughout the irrigation season.

Soil Moisture Storage--
Soil moisture storage refers to the capacity of the soil to hold water. When irrigation occurs, the soil moisture reservoir is usually filled to capacity to replace water which has been lost to evapotranspiration. Excess root-zone diversions pass below the root zone as deep percolation. Root-zone diversions are all of the water which has infiltrated into the soil profile. Field capacity and permanent wilting points should be established for each soil type in the project area, and bulk density determinations should be made with respect to depth. Holmes et al. (1967) present a good discussion on methods and procedures for obtaining soil moisture data.

Methods of measuring and monitoring soil moisture include gravimetric (weighing--drying--reweighing) water and calcium carbide reaction methods (for example, "SPEEDY" meter), or by indirect methods such as tensiometers and gypsum resistance blocks. Information on these methods is contained in Richards (1954), Black et al. (1965), and Oster et al. (1976). Tensiometers and resistance blocks should not be used in saline conditions. Soil salinity can be monitored by soil sampling and laboratory analysis (Black et al., 1965) and by the use of salinity sensors (Oster and Willardson, 1971; Oster et al., 1976). Soil samples should be taken immediately before each irrigation and again when soil is at field capacity, which is usually twenty-four to forty-eight hours after the irrigation event. It may often be necessary to take a series of soil samples after an irrigation event until the soil moisture "levels" off to establish field capacities.

Irrigation Management Analysis--

Irrigation management can greatly influence the pollution contribution from a given field. Frequently, the majority of pollution can be alleviated by improved irrigation management practices. Van Schilfgaarde et al. (1974) discussed irrigation management for salinity control.

Evapotranspiration and the soil moisture deficit, or soil moisture tension, dictates when an irrigation event should occur. Considering the leaching requirements as a function of the quality of irrigation water and soil salinity, these parameters indicate the proper depth to be applied, and hence the time duration of each irrigation set.

The adequacy of the irrigation is a comparison of what should have been done with what actually occurred, and where improvements could be made. Examples of this type of analysis are presented in Skogerboe et al. (1974a) and Evans et al. (1978b). Other considerations to assess the adequacy of the irrigation include nutrient losses, leaching or surface runoff; erosion problems; areas of deposition and degradation; tailwater reuse; power consumption; as well as many other considerations that may be of local concern.

Irrigation costs can also be a major factor in choosing acceptable alternatives for pollution control activities. The costs of labor, capital, energy, crop yields, farm income, and annual farm and irrigation system operation and maintenance must be considered in selecting any potential solution. Sheffield (1977), Reed et al. (1977), New (1977), Wilson et al. (1976), Pitchford and Wilkinson (1975) and others discuss the economic decisions and evaluations of irrigation systems. It should be remembered that agricultural economics and crop yields are very sensitive to local conditions.

WATER REMOVAL SUBSYSTEM INVESTIGATIONS

Head Ditch Seepage

Since each field or farm must be evaluated individually, the time distribution of on-farm water use is very critical in the analysis of the water removal subsystem. These data must be collected in the field if good data are not available from other sources. For example, water is usually in a head ditch less than 50 percent of the growing season. The effectiveness of already lined, or of lining unlined head ditches, or replacing them with other means such as gated pipe cannot be assessed without knowing how and when these ditches are in use.

Deep Percolation

Deep percolation is probably the most difficult and elusive segment of the hydro-salinity study to define. It is usually a residual calculation and, as such, it contains the errors of all the other measurements. The total deep percolation is a fairly small quantity, usually less than 10 to 30 percent of the total field diversions, and since the errors from all the other components of the hydrologic budget tend to be additive, it may be in error by 100 percent or more. If water balance techniques are to be used, with deep percolation being calculated, it is critical that every effort be made to minimize the error of the other terms.

Duke and Haise (1973) developed a method for the direct measurement of deep percolation quantity and quality using vacuum extractors (Figure 51). This method is much more accurate than many of the other procedures. These installations are fairly expensive ($1000-$2000 each), and they should be installed and used by qualified personnel.

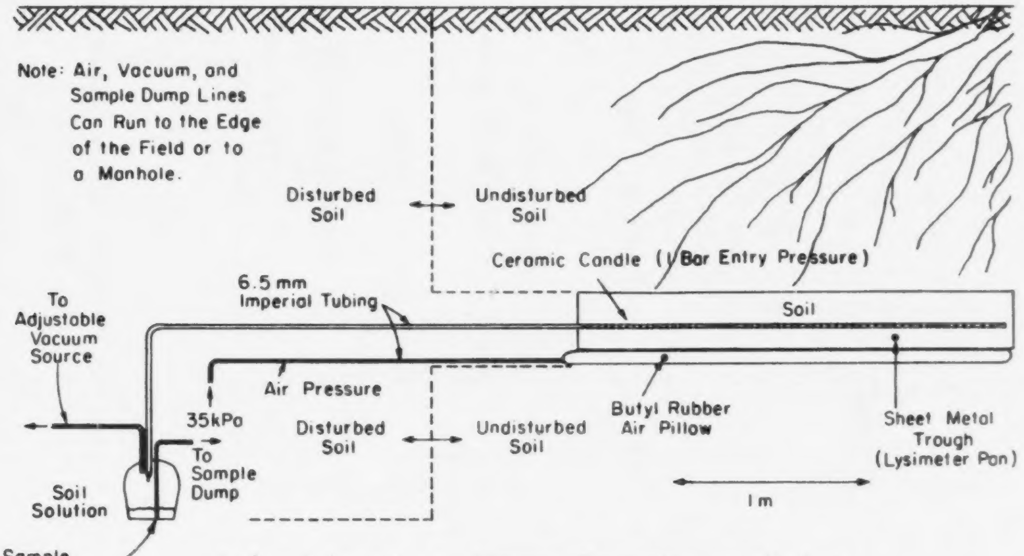
Methods using the concentration of conservative ions with depth in the soil profile as tracers are fairly inexpensive and usually reliably indicate the quantity of deep percolation. Suitable conservative ions should be water soluble, not used by the plants, and unaffected by cation exchange reaction in the soil. The most commonly used ion for these investigations is chloride (Cl^-). The analysis and use of this method is discussed by van Schilfgaarde et al. (1974), Bernstein and Francois (1973), and Rhoades et al. (1973). The chemical analysis is discussed by Richards et al. (1954), Black et al. (1965) and Lusczynski (1961). The bromide (Br^-) ion has also been used as a suitable tracer (Wendt et al. 1976).

An inexpensive method for the collection of soil-water quality samples with depth is a pressure-vacuum lysimeter (Figure 52). These devices use an unglazed porous ceramic cup attached to a piece of plastic pipe for a sample collection area. These units are sealed and a vacuum is maintained to collect a sample. To extract the sample, positive pressure is applied and the sample removed. These lysimeters are usually buried in several locations across a field at various depths. More information on this method can be obtained from Parizek and Lane (1970), Wagner (1962), Grover and Lamborn (1970), Wood (1973), and Wengel and Griffen (1971).

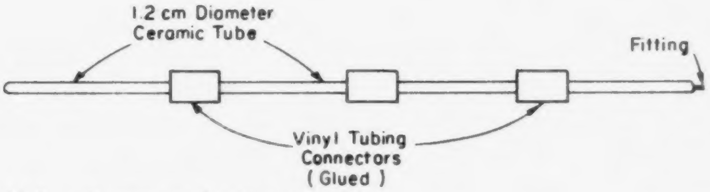
Drainage Investigations

There are basically three types of drainage systems for agricultural use. These are interceptor drains, relief drains, and pump drains. All are installed to lower the water table to provide proper aeration in the crop root zone and/or provide an effective leaching mechanism for the control of soil salination. As such, drainage system effluents are very often quite saline. Rhoades (1974) and Skogerboe et al. (1974b) discuss the importance of drainage for salinity control.

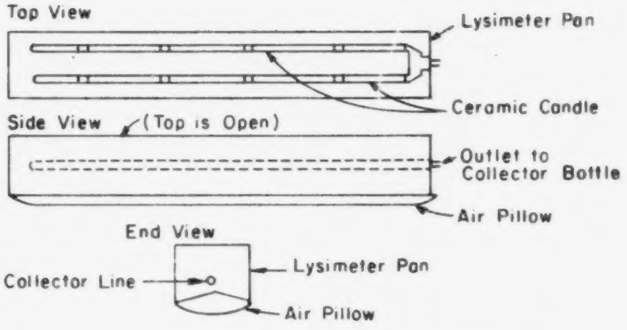
To determine the effectiveness of existing drainage systems or to determine the design requirements of new systems, it is necessary to collect sufficient field data. Data required for most drainage evaluations vary with the computer models to be used, but will usually include drain spacing,


Note: Air, Vacuum, and Sample Dump Lines Can Run to the Edge of the Field or to a Manhole.
Disturbed Soil
Undisturbed Soil
Ceramic Candle (1 Bar Entry Pressure)
Soil
6.5 mm Imperial Tubing
To Adjustable Vacuum Source
Air Pressure
35kPa
To Sample Dump
Disturbed Soil
Undisturbed Soil
Butyl Rubber Air Pillow
Sheet Metal Trough (Lysimeter Pan)
1 m
Soil Solution
Sample Collection Bottle

(a) Schematic of Vacuum Extractor Installation

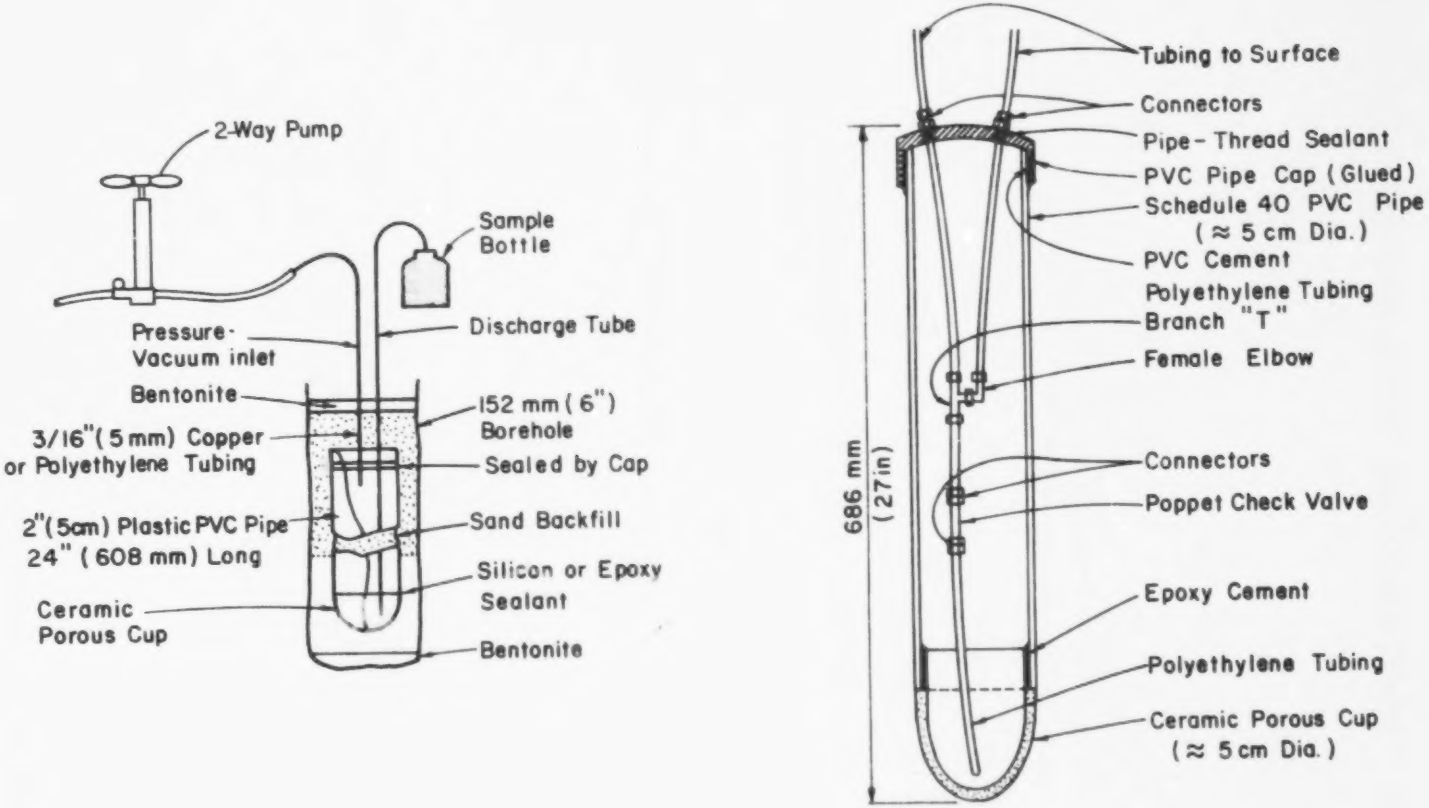

1.2 cm Diameter Ceramic Tube
Fitting
Vinyl Tubing Connectors (Glued)

(b) Ceramic Candle Detail


Top View
Lysimeter Pan
Ceramic Candle
Side View
(Top is Open)
Outlet to Collector Bottle
Air Pillow
End View
Collector Line
Lysimeter Pan
Air Pillow

(c) Lysimeter Pan Detail

Figure 51. Schematic of vacuum extractors installation with detail.


2-Way Pump
Sample Bottle
Pressure-Vacuum inlet
Discharge Tube
Bentonite
152 mm (6") Borehole
3/16"(5 mm) Copper or Polyethylene Tubing
Sealed by Cap
2"(5cm) Plastic PVC Pipe 24" (608 mm) Long
Sand Backfill
Silicon or Epoxy Sealant
Ceramic Porous Cup
Bentonite
Tubing to Surface
Connectors
Pipe-Thread Sealant
PVC Pipe Cap (Glued)
Schedule 40 PVC Pipe (≈ 5 cm Dia.)
PVC Cement
Polyethylene Tubing
Branch "T"
Female Elbow
Connectors
Poppet Check Valve
Epoxy Cement
Polyethylene Tubing
Ceramic Porous Cup (≈ 5 cm Dia.)
686 mm (27 in)

Cross Section of a Typical Pressure - Vacuum Lysimeter Installation (Parizek & Lane, 1970)

Modified Pressure - Vacuum Lysimeter Installation (Wood, 1973)

Figure 52. Schematic view of pressure-vacuum lysimeters for soil water quality sample collection.

depth, size, envelope thickness, soil hydraulic characteristics, time distributed effluent, and influent water quality and quantity. It is often necessary to obtain soil hydraulic properties including initial moisture conditions, apparent saturated hydraulic conductivity, and infiltration functions. Corey (1977), Boersma (1965), Klute (1965), and Bouwer and Jackson (1974) are good references on the direct and indirect procedures and methods of determining these data.

Groundwater Monitoring Techniques

Todd et al. (1976) presents an excellent discussion on the methodologies of groundwater monitoring techniques. A general indication of the costs of various groundwater monitoring and evaluation techniques is presented by Everett et al. (1976). Tinlin (1976) presents several illustrated examples of monitoring groundwater pollution sources, one of which is concerned with subsurface agricultural return flow.

The most common devices for hydrologic measurements of groundwater are the combined use of observation wells and piezometers. Observation wells are used to provide information on the water table depth at a location. Wells are perforated throughout the saturated thickness of the aquifer, and as such, provide a vertical integration of the aquifer properties and water quality. Piezometers, on the other hand, are not perforated and are only open at the extreme ends. Piezometers are used when vertical gradients in an aquifer are needed and when it is desirable to obtain the hydraulic properties at a point. Clusters of piezometers can also be used to collect water samples with depth so that concentration profiles may be determined. The depth from the top of the casings to the water in the wells and piezometers should be obtained at least weekly, and water samples should be extracted at least once a month for water quality analyses. The observation wells are usually a small diameter (5 to 10 cm) and are cased with either steel or heavy plastic perforated pipe (Figure 53). Benz et al. (1963), Donnan and Bradshaw (1952), Myers and van Bavel (1962), the United States Department of Interior, United States Bureau of Reclamation (1964), United States Department of Agriculture, Soil Conservation Service (1973), and Johnson Division of Universal Oil Products (1972) describe the general placement and evaluation procedures for observation wells.

Observation wells are usually installed on a grid system. It may be necessary to have a professional well driller install these wells. To facilitate identification of the types and composition of the individual strata, their thickness, and the thickness of the total aquifer, a driller's log is a minimum requirement. More complete data is often needed for analyses than can be obtained from a driller's log, in which case "self-potential" (SP), apparent resistivity and gamma rays or other types of logs can be required (Figure 54).

In stratified aquifers it is often necessary to install observation wells in a cluster arrangement. Several wells can be installed in one large bore hole or the wells can be individually installed (Figure 55). Shallow wells, less than 5 meters, can also be installed by project personnel when the well casing can be driven using a well point or a small drilling rig.

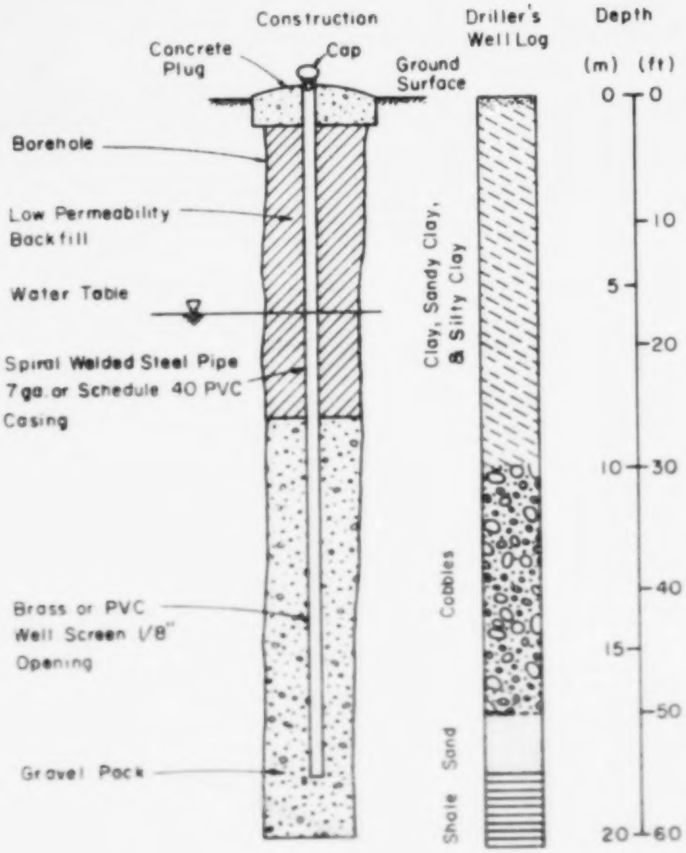

Construction
Concrete Plug
Cap
Ground Surface
Driller's Well Log
Depth
(m) (ft)
Borehole
Low Permeability Backfill
Water Table
Spiral Welded Steel Pipe 7 ga. or Schedule 40 PVC Casing
Brass or PVC Well Screen 1/8" Opening
Gravel Pack
Clay, Sandy Clay, & Silty Clay
Cobbles
Sand
Shale
0
5
10
15
20
0
10
20
30
40
50
60

Figure 53. Sketch of typical observation well construction and the associated driller's log.

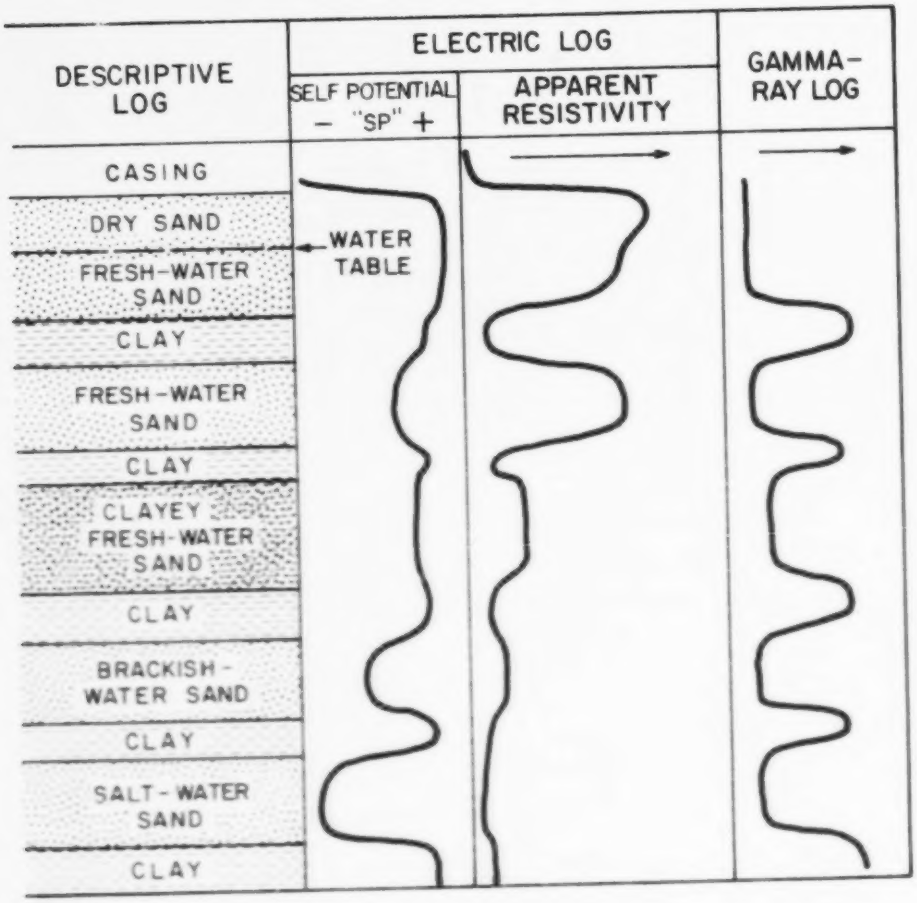

ELECTRIC LOG
DESCRIPTIVE LOG
SELF POTENTIAL
− "SP" +
APPARENT RESISTIVITY
GAMMA-RAY LOG
CASING
DRY SAND
WATER TABLE
FRESH-WATER SAND
CLAY
FRESH-WATER SAND
CLAY
CLAYEY FRESH-WATER SAND
CLAY
BRACKISH-WATER SAND
CLAY
SALT-WATER SAND
CLAY

Figure 54. Representative geologic, electric, and gamma-ray logs that are used for the identification of the hydrologic properties of the geologic substrata. (Johnson Division of Universal Oil Products, 1972).

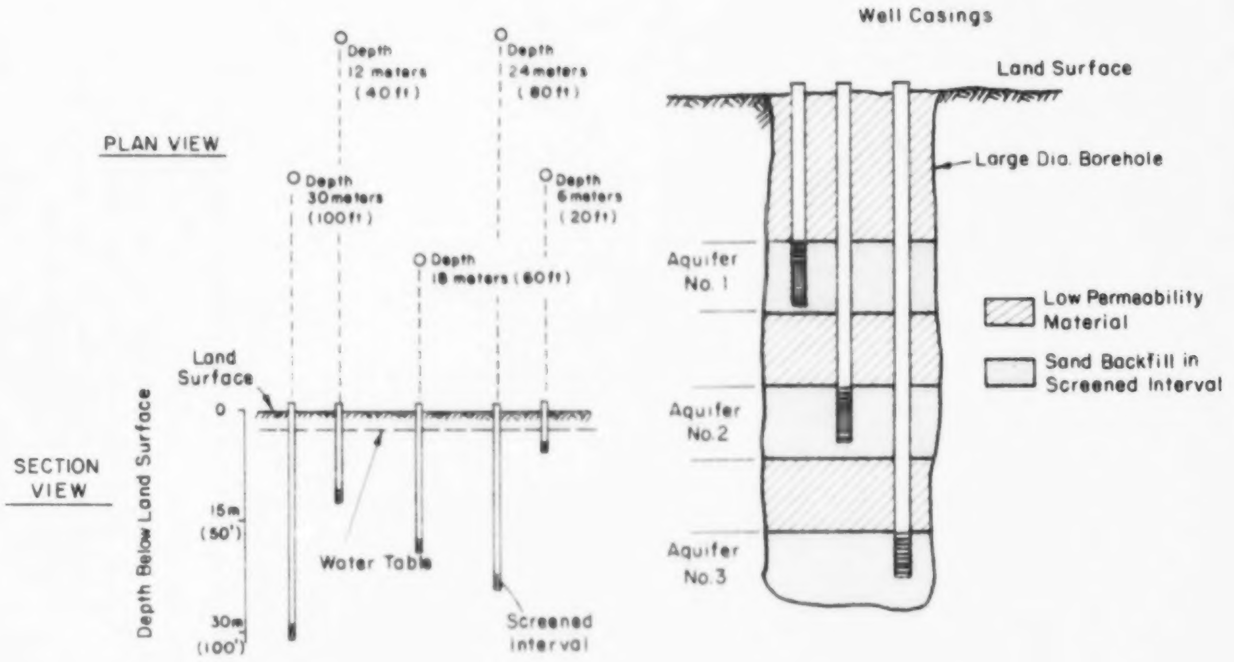

PLAN VIEW
SECTION VIEW
Depth 12 meters (40 ft)
Depth 24 meters (80 ft)
Depth 30 meters (100 ft)
Depth 6 meters (20 ft)
Depth 18 meters (60 ft)
Land Surface
Depth Below Land Surface
0
15m (50')
30m (100')
Water Table
Screened interval
Well Casings
Land Surface
Large Dia. Borehole
Aquifer No. 1
Aquifer No. 2
Aquifer No. 3
Low Permeability Material
Sand Backfill in Screened Interval

Figure 55. Schematic representation of observation well clusters for stratified aquifer situations.

Obviously, driller's log information would not be obtainable from this type of installation. Campbell and Lehr (1973) present more information concerning water well drilling techniques and well development.

After the wells are installed, data can be collected on the hydraulic conductivity, specific yield and storage coefficients, transmissibility, and other values. Each well should be provided with a threaded cap to keep debris from natural sources or vandalism from destroying the usefulness of the wells. The wells should be periodically flushed to ensure representative flows and water quality information.

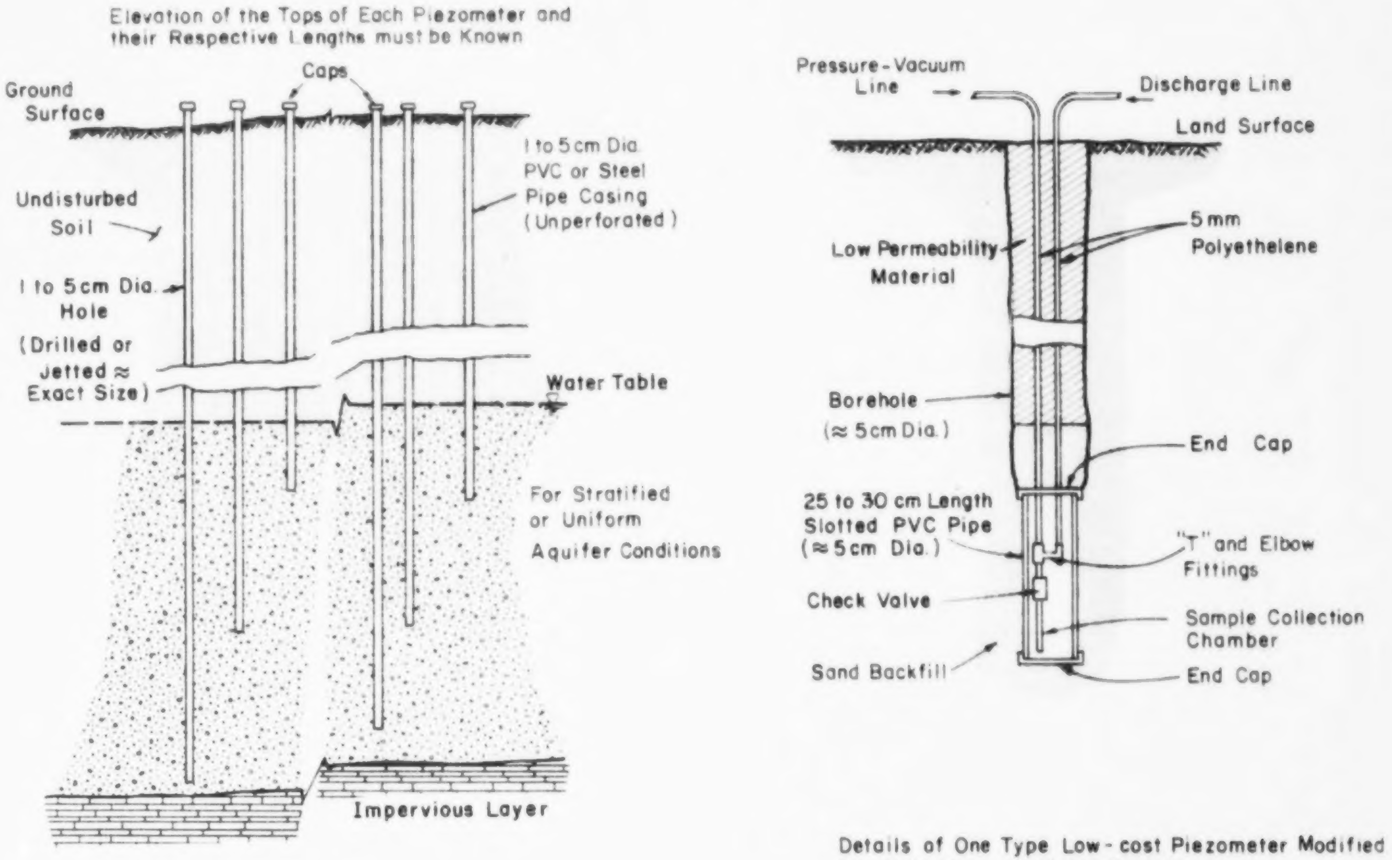
Piezometers are usually small diameter nonperforated pipes about 1 to 2 cm (3/8 to 3/4 inch) in diameter (Figure 56). Piezometers measure the hydraulic gradient of the aquifer at the depth of the end of the piezometer. Piezometers are also used to collect water quality samples for laboratory analysis. Piezometers are also installed on a grid system that is usually close to the observation wells and in a cluster arrangement. Under good conditions with few large rocks, piezometers can often be installed by project personnel by use of a jetting rig. The jetting rig forces water through the piezometer pipe as it is pushed into the ground (Mickelson et al., 1961; Donnan and Bradshaw, 1952). The force of the water jet removes unconsolidated particles. Piezometers may often be driven into place. Information on the installation measurement and evaluation of piezometers is presented by the United States Department of Interior, United States Bureau of Reclamation (1964), Reeve and Jensen (1949), Bornstien and Alberts (1963), Myers and van Bavel (1962), and Donnan and Bradshaw (1952).

When selecting sites for observation wells and piezometer installations, they should be located where vehicular traffic, farming equipment, or road maintenance equipment will not disturb or remove the upper portions of the pipes. A good location is very often found in a fence row.

The water levels for piezometers and wells are usually measured from the top of the pipe to the water level. To tie together all of the data from all of the wells and piezometers in a grid system, it is necessary to determine the elevations of the tops of each well and piezometer casing, and thereby the respective water level elevations for each well and piezometer.

Another method often used in groundwater studies is radioactive tracers such as bromide isotopes (Jester et al., 1977; Jester and Uhler, 1974) to indicate flow velocities, quantities, and direction of flow. It is often very difficult to interpret these data, and it is not recommended for use except by experienced personnel.

Equipment for water sampling and depth to water determinations are commercially available from organizations such as Soiltest Inc. (2205 Lee Street, Evanston, Illinois 60202). It often becomes necessary to construct equipment to meet the specific requirements of the project installations. Some specialized equipment for water sampling are presented by Hansen and Harris (1974) and Cherry (1965).


Elevation of the Tops of Each Piezometer and their Respective Lengths must be Known
Caps
Ground Surface
Undisturbed Soil
1 to 5cm Dia. Hole
(Drilled or Jetted ≈ Exact Size)
1 to 5cm Dia PVC or Steel Pipe Casing (Unperforated)
Water Table
For Stratified or Uniform Aquifer Conditions
Impervious Layer
Pressure-Vacuum Line
Discharge Line
Land Surface
Low Permeability Material
5mm Polyethelene
Borehole (≈ 5cm Dia.)
End Cap
25 to 30 cm Length Slotted PVC Pipe (≈ 5cm Dia.)
"T" and Elbow Fittings
Check Valve
Sample Collection Chamber
Sand Backfill
End Cap

Details of One Type Low-cost Piezometer Modified For Collection of Water Sample

Series of Typical Piezometer Installations

Figure 56. Typical piezometer installations that can be used for vertical water gradients and water quality information.

Very often local consulting engineering firms, local government engineering service agencies, state engineers' offices and the local United States Geological Survey office will have information on the hydraulic properties of the aquifers in the area. The United States Geological Survey also has numerous publications such as Johnson (1966) that are beneficial in estimating hydraulic parameters for an area, and extending the results of a project area to cover the entire irrigated portion.

SECTION 9

DEVELOPING BEST MANAGEMENT PRACTICES

ALTERNATIVE MANAGEMENT PRACTICES

Results from hydro-salinity and detailed simulation models calibrated and verified by research and/or demonstration programs provide considerable insight as to which technologies might be most appropriate in reducing subsurface return flows. Goals considered in reducing subsurface return flows may include: (a) lowering groundwater levels to alleviate waterlogging, thereby allowing the leaching of salts in the root-zone to increase crop production; (b) reducing downstream water quality degradation resulting from salt pickup; and (c) improving on-farm water management to increase crop production. Specifically, the array of potential practices noted in Section 4 that can be applied in an irrigated region to improve the quality of irrigation return flows or reduce the impact of these discharges on receiving waters, might include structural changes (canal and lateral linings, drainage, land leveling, and conversion to more suitable irrigation methods) and improved irrigation practices. For instance, providing the irrigator with an irrigation scheduling service to help maximize the water application efficiency would diminish the volume of irrigation return flows. Various other improvements in designs or practices might be noted, some of which would be more applicable than others to the multitude of conditions existing in irrigated areas in the western United States. Various nonstructual changes such as land retirement, taxation, influent or effluent controls should also be considered and the results quantified.

Environmental Protection Agency Rules and Regulations (40CFR 130.1 (q)) define best management practice as "a practice or combination of practices determined by a State or other management agency after problem assessment, examination of alternative practices and appropriate public participation to be the most effective, practicable means of preventing or reducing the amount of pollution generated by nonpoint sources to a level compatible with water quality goals." "Practicable" is defined as being feasible, based on technological, economic and institutional considerations. Best management practices are intended to meet both temporary and permanent pollution control needs to minimize erosion, salinity, sedimentation and other types of water quality degradation. The particular best management practices must be determined and developed according to site-specific requirements.

ANALYSIS OF FIELD DATA

Costs associated with water quality problems and the measures necessary for their resolution are generally high, particularly when the problem results from irrigated agriculture. It is important to implement only the management alternatives that promise the most cost-effective treatment of the problem, subject to environmental and political constraints. The ultimate use of research and demonstration data is in determining the best management practices to be implemented for the solution to the specific salinity problems identified for the basin area under study.

If the project is such that no improvements or demonstration programs are constructed prior to the large-scale implementation, materials and installation costs must be obtained from other sources. Reliable cost information for larger sizes (10 cfs or greater) of various types of canal lining, closed conduits and water control structures can be obtained from agencies such as the United States Bureau of Reclamation and the United States Corps of Engineers. Fairly accurate and representative costs for smaller delivery system components, as well as various on-farm and drainage improvements, can be obtained from local irrigation equipment suppliers and manufacturers.

To extend the costs to the entire irrigated area to be treated, it is necessary to collect information for the area concerning farm sizes, field areas, lengths, and widths, field slopes, lateral lengths and acreages served by each lateral, and canal and lateral capacities and cross-sections at several points in the delivery systems. To delineate the types of on-farm improvements that could be implemented, it is necessary to collect information on infiltration rates, cropping patterns, depth of top soil, and localized problems such as high water tables or soil fertility levels. Some of this information can be taken from aerial photographs or detailed farm maps, but much of the information must be collected in the field via actual measurements and personal interviews with farmers and local irrigation company officials. Open personal communications and periodic project reviews by as many local persons as possible can lend valuable insight into possible economic and sociological ramifications of the project.

Collection of the information necessary to extend the costs for a study area or an entire irrigated system, which is basically a preliminary design analysis, is facilitated by the use of aerial photographs for the area. The United States Agriculture Stabilization and Conservation Service maintains a fairly current inventory of aerial photography for most irrigated areas. Commercial aerial photography services may also be a source of photographs. Also, if vegetative mapping is to be done, it may be necessary to have two sets of photographs for the areas. Both sets of photos should have the same scale in order to facilitate data analysis.

Preliminary design information may be gathered by personal inspection of the farm lateral systems. Data may be collected by marking on each photograph information concerning land ownership, diversion points for the canals, laterals, and farm distribution systems; ditch lengths and dimensions; locations of special hydraulic structures such as measurement devices, flow division locations, culverts, siphons, and bridges; the location and quantities of return flows; locations of pumps; special problem areas such as buried utilities, trees that might have to be removed, hazardous areas requiring special safety considerations, areas requiring fill dirt, and areas that may require flood protection facilities. When these data have been collected, an inventory or tabulation method must be devised to summarize all of the information into a usable form.

COST-EFFECTIVENESS ANALYSES

Cost-effectiveness functions should be developed for each appropriate technology that can be identified. Then, cost-effectiveness functions should be developed for each combination of appropriate technologies. These cost-effectiveness functions that relate subsurface return flow reductions to the desired goals resulting from a specified investment, would then be assessed in an optimizational format to arrive at the least-cost combination for achieving a desired level of the stated salinity reduction goals. This analysis details the optimal strategy for implementing various levels of individual technological improvements into a comprehensive technology package.

On a basin-wide scale, a salinity problem is the combined effect of many irrigated areas, saline springs, diffuse natural inflows, and other miscellaneous sources. These salinity sources not only occur sequentially due to the geographic structure of a hydrologic area, but are often governed by differing administrative structures. The problem of determining an "optimal" strategy for a large river basin rapidly becomes too large and too complex for direct analysis. One of the various mathematical techniques for optimizing complicated systems is to decompose the problem into a series of subproblems with solutions coordinated in a manner that produces an answer to the larger problems. One method applied to analysis of water quality improvements in the Utah Lake drainage basin of central Utah provides both a simple and effective method of decomposition (Walker et al., 1973; Walker, 1978a). The structure of the decomposition methodology referred to above is shown schematically in Figure 57. Individual levels of modeling define water quality cost-effectiveness analyses at that level enroute to the most cost-effective water quality control program on a basin-wide scale.

Conceptual Salinity Control Model

The conceptual model illustrated in Figure 57 represents an additive approach for determining the minimal cost salinity control strategy in a river basin. A number of levels or subdivisions having similar characteristics can be defined to correspond to various levels of hydrologic or administrative boundaries in a region. Within each level, the alternative measures for salinity management are characterized by cost-effectiveness relationships. A more detailed review of the structure of cost-effectiveness functions and their interdependence assist in understanding the application of the conceptual model.

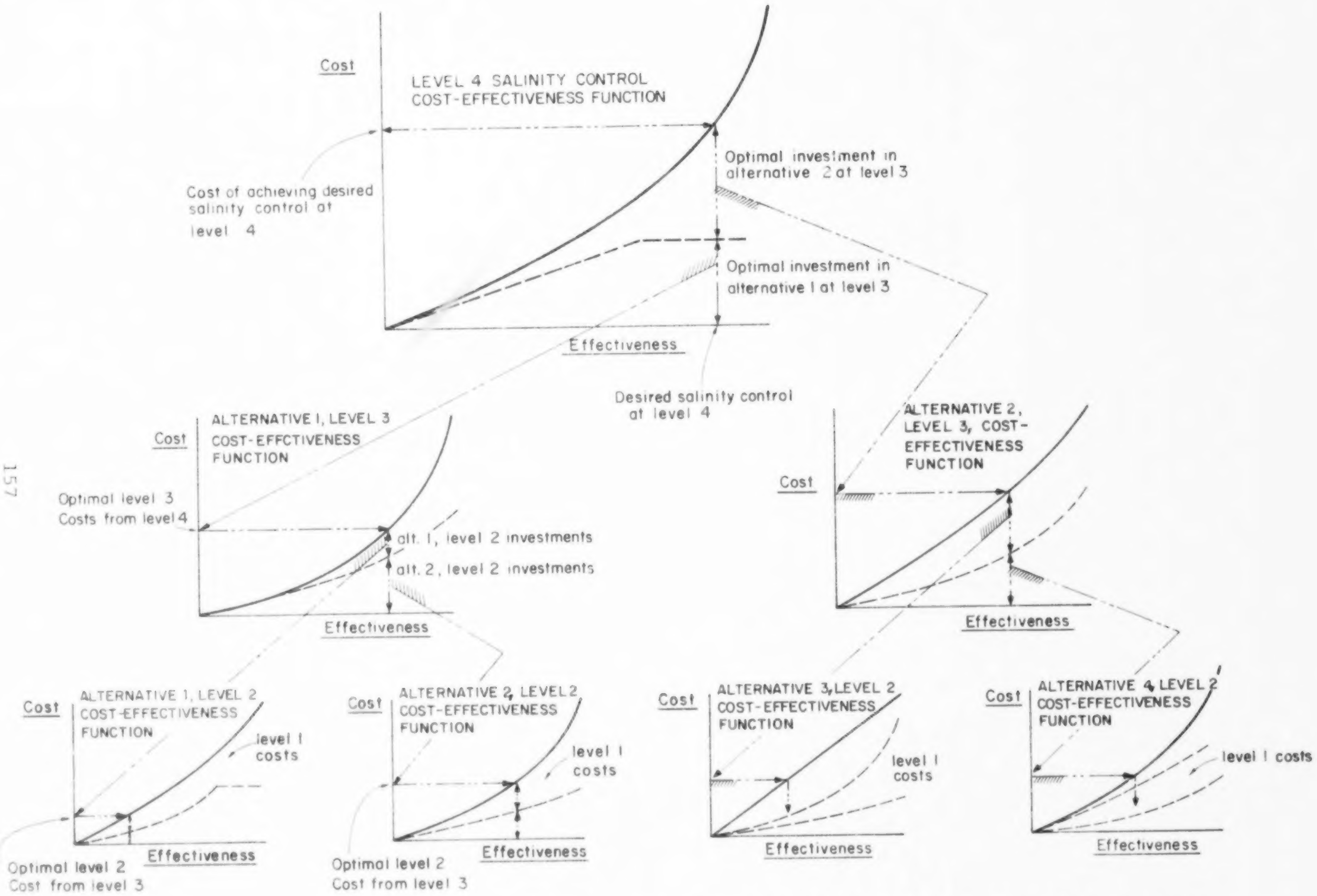

Cost
LEVEL 4 SALINITY CONTROL COST-EFFECTIVENESS FUNCTION
Cost of achieving desired salinity control at level 4
Optimal investment in alternative 2 at level 3
Optimal investment in alternative 1 at level 3
Effectiveness
Desired salinity control at level 4
ALTERNATIVE 1, LEVEL 3 COST-EFFCTIVENESS FUNCTION
Cost
Optimal level 3 Costs from level 4
alt. 1, level 2 investments
alt. 2, level 2 investments
Effectiveness
ALTERNATIVE 2, LEVEL 3, COST-EFFECTIVENESS FUNCTION
Cost
Effectiveness
Cost
ALTERNATIVE 1, LEVEL 2 COST-EFFECTIVENESS FUNCTION
level 1 costs
Optimal level 2 Cost from level 3
Effectiveness
Cost
ALTERNATIVE 2, LEVEL 2 COST-EFFECTIVENESS FUNCTION
level 1 costs
Optimal level 2 Cost from level 3
Effectiveness
Cost
ALTERNATIVE 3, LEVEL 2 COST-EFFECTIVENESS FUNCTION
level 1 costs
Effectiveness
Cost
ALTERNATIVE 4, LEVEL 2 COST-EFFECTIVENESS FUNCTION
level 1 costs
Effectiveness

Figure 57. Conceptual decomposition model of a regional or basin salinity control strategy (Walker, 1978a).

Description of Cost-Effectiveness Functions--

The alternatives for managing salinity on a basin-wide scale fall into two categories: (a) those that reduce salinity concentrations by dilution, or minimizing the loss or pure water from the system by evaporation; and (b) those that improve water quality by reducing the mass emission of salt. Examples of the first category include weather modification to enhance stream flow, evaporation suppression, and phreatophyte control. Many of these approaches may be more costly and difficult to apply than is justified by the salinity control achieved. In the second category, such measures as saline flow collection and treatment, reduction in agricultural return flows, and land use regulation can be used to reduce the total emission of salinity entering receiving waters.

By letting the spatial scale of the problem correspond to successive layering or additions, the multilevel approach is congruent to the subbasin breakdown of major hydrologic areas. The smallest spatial scale considered in this kind of analysis should be a subbasin containing an irrigated valley, or a stream segment delineated by inflow-outflow analysis. In a major river basin, a number of subbasins may combine to form the basin itself so there are actually three levels to be considered in a river basin. Vertical integration of subbasins yield the aggregate river basin. In this analysis, the river basin, river subsystem, and subbasin divisions are designated as levels 4, 3, and 2, respectively. Level 1 also encompasses the subbasin scale as described later.

Associated with each level of the model are cost-effectiveness functions describing each alternative for controlling salinity. The structure of the cost-effectiveness functions includes two parts. The first is the function itself. To compare the respective feasibility among various salinity control measures at each level, the mathematical description of each alternative must be in the same format. Since most planning studies involve evaluating the minimal cost strategy for reducing salt loading, each salinity control measure's feasibility for inclusion in the eventual strategy is based on its resulting reduction in salt loading. The second part of the cost-effectiveness functions is what might be called a "policy space." To appreciate this aspect of the model, it is helpful to first discuss the determination of the optimal basin-wide strategy.

Evaluating the Optimal Strategy--

Providing the optimal policy for controlling salinity in a river basin was determined with a minimum cost decision criterion. The analysis provides two pieces of information. First, it details the cost associated with a range of reductions in salinity, and second, it delineates how much of these costs would be expanded in each river subsystem. In other words, the evaluation of the optimal strategy at level 4 involves systematic comparison of level 3 cost-effectiveness functions; and once the strategy has been determined, it also yields the optimal costs or expenditures in each level 3 alternative or river subsystem. Similarly, level 2 costs and policies are determined during the level 4 analysis, and so on. Thus, the cost-effectiveness function for any alternative within a level is:

1. The result of optimization of respective cost-effectiveness functions at a lower level, and therefore, a minimum cost relationship at every point; and

2. The sum of costs from optimal investments into each alternative at a lower level. The "policy space" is, therefore, a delineation of lower level cost-effectiveness functions.

The preceding paragraphs note the detailing of a salinity control strategy once the optimal is known. Determining the basin optimal, on the other hand, begins at level 1. A comparison of level 1 cost-effectiveness functions describing each alternative at that level produces the array of level 2 functions. Similar steps yield each succeeding level's optimal program. Thus, the multilevel approach described herein involves a vertical integration through the levels to determine the optimal policy and a backwards trace to delineate its components.

The most detailed cost-effectiveness function referred to above is the level 1 analysis of individual salinity control measures which can be applied in a subbasin. In this report, the primary emphasis is on salinity problems due to salt pickup in irrigated agriculture. Consequently, it should be helpful to mention a few items relative to the level 1 analysis of irrigated agriculture.

The major first level salinity control options in an irrigated area are the: (a) construction of conveyance channel linings to reduce or eliminate seepage; (b) improvement of irrigation practices to minimize deep percolation; (c) collection and desalination of drainage flows; (d) selective retirement of irrigated lands to eliminate deep percolation; (e) employment of economic incentives such as subsidies or taxation to induce salinity reduction measurements; and (f) imposing of legal effluent or influent limitations to force more efficiency in irrigation water use. Each of these alternatives has one or more specific components that require evaluation. For instance, the most cost-effective conveyance channel lining, or the best on-farm control measure, must be determined. The first cost-effective modeling level is also the result of a lower level optimization or the zero level. At this level of analysis, it is difficult to generate adequate cost-effectiveness functions without pilot field demonstrations and evaluation of the alternatives. During planning studies, field investigations are generally not conducted and the investigators must rely on reported distributions of costs and effects. Walker (1978a) gives a dimensionless distribution of costs and salinity reductions for the first level alternatives (Figure 58). These curves can be utilized in planning studies to arrive at the Level 1 cost-effectiveness functions without actual field studies. These curves, however, were developed for the Grand Valley in western Colorado and will introduce errors if conditions vary greatly from those for which the curves were formulated.

To use Figure 58, it is first necessary to estimate the total cost of implementing each measure to its maximum effectiveness. The salinity reduction associated with this level of investment must also be estimated. Then, an expression describing curves in Figure 58 can be used to calculate the range of costs for reducing salinity by each measure up to the

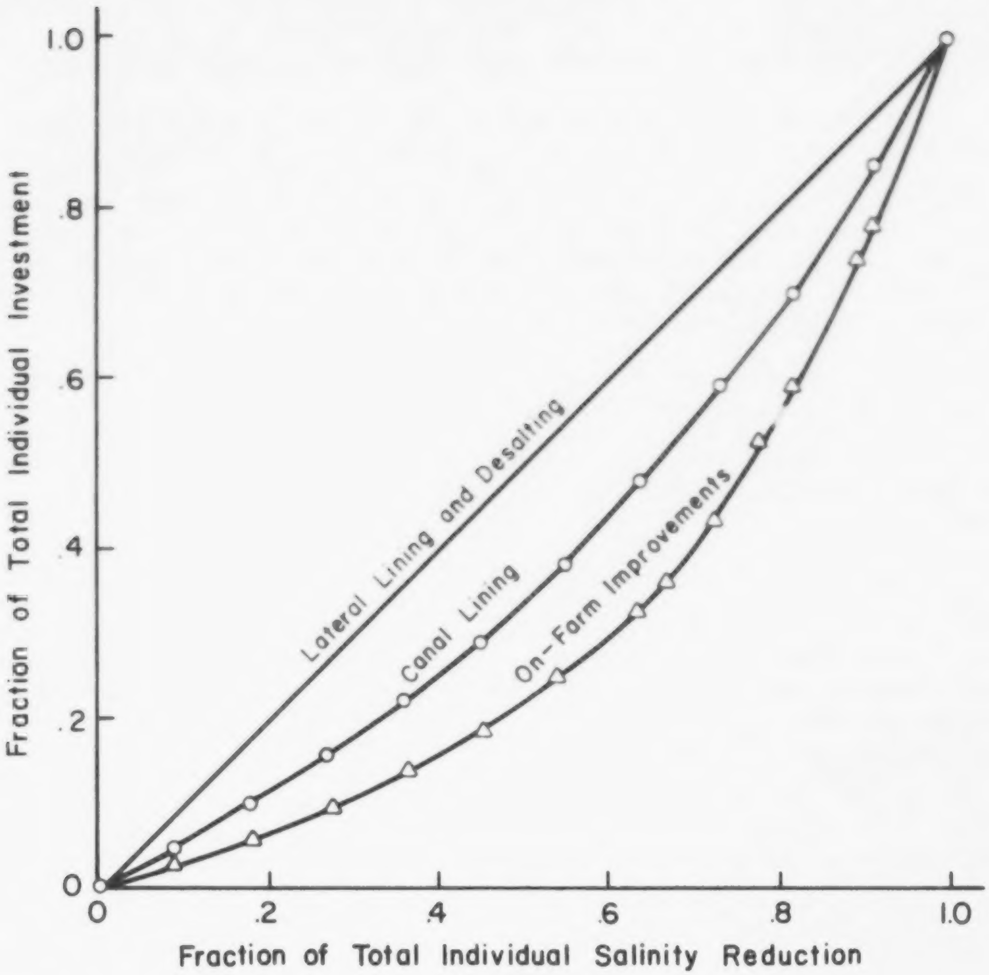


Figure 58. Dimensionless level 1 cost-effectiveness curves for the Grand Valley (Walker, 1978a)

maximum possible. Figure 58 represents the expected distribution of cost-effectiveness for the salinity alternatives included.

SECTION 10

IMPLEMENTATION OF BEST MANAGEMENT PRACTICES

INTRODUCTION

The program for implementing best management practices should promote social and economic benefits through cooperative action. Every effort should be made to prevent polarization between state and federal water pollution control agencies, organizations providing technical assistance during implementation, and local water users. A necessity exists to develop credibility among all institutions involved with the individual farmers. In order for a comprehensive salinity control program to be successful, active farmer participation is required.

There are many legal and economic considerations involved with implementation, as well as questions regarding organization. Besides the actual construction of improvements, there are aspects of training, technical assistance and farmer participation that are important for facilitating implementation. Lastly, since all solutions are never known, it becomes essential to continually evaluate and refine the implementation processes.

LEGAL CONSIDERATIONS

Beneficial Use

A major legal problem that is universal throughout the 17 western states is the failure to enforce the beneficial use provisions in the law. The reason is twofold. First, the definition of beneficial use is nebulous and, thus lacks appropriate direction for administrators to follow or the courts to interpret. The second reason is derived from a lack of social consciousness on the part of water users so the burden of proving nonbeneficial use is upon the state, which is an administrative impossibility. Generally, the system of water law places emphasis upon the *right* to use water, not the *duty* to use it appropriately.

Court cases in Colorado and other western states reflect the difficulty of enforcing the general concept of beneficial use. It is suggested that State Engineers Offices develop and adopt criteria for enforcing beneficial use as an agency regulation, particularly for those irrigated areas where water quality problems are significant. Regulation should define standards for the conveyance and application of water relative to the quantity of diversions, water use, and quality of discharge. The State Engineer must also provide the authority for shifting the burden of proper water use upon the benefactor (both purveyor and user), and identify the quantity of water necessary or the water duty for delivery, use, and removal of water.

Influent Standards

Along each irrigation canal, turnout gates discharge water into a lateral. This turnout gate is a critical control point in the irrigation system because it represents the termination of responsibility for many irrigation companies. The control point for each irrigation company is the point of diversion from a river. The responsibility for these river diversions belongs to a water commissioner or river commissioner who is usually a state employee. The amount of water discharged at each turnout gate along a canal is the responsibility of water masters or ditch riders who are employees of the irrigation company or district.

Proper operation of an improved lateral subsystem results in significant reductions in the discharge requirement at the turnout gate. Since the lateral turnout gate is an important control point, standards for water use could be enforced at each turnout gate, which could be classified as an influent pollution control standard. An initial influent standard should be the intended water duty for the irrigated lands as a result of implementing best management practices. This standard should be measured at each farm inlet, which can then be translated back to the lateral turnout gate taking into consideration some small administrative losses and lateral seepage losses, which essentially could be ignored if the laterals were lined or converted to pipelines. An important consideration would be to use either a volumetric water duty as a standard or a variable flow rate which is dependent upon the changing water requirements of the crops during an irrigation season.

By using influent standards, the salinity problem is alleviated by improved water management practices, rather than end-of-pipe treatment, which would be the result of using effluent standards under a permit program. The success of an influent approach is dependent upon: (a) use of numerous flow measuring devices; (b) adequate technical assistance for working with and advising farmers on improved irrigation practices and methods; and (c) availability of funds for making the necessary structural improvements.

ECONOMIC CONSIDERATIONS

Cost Sharing

Historically, the Agricultural Conservation Program, administered under the U.S. Department of Agriculture, with technical assistance provided by the Soil Conservation Service, has provided cost-sharing funds to farmers and irrigation districts for irrigation system improvements. The program had water quality benefits which were never verified or documented. This program has been relatively inactive in recent years because of insignificant funds. However, with recent congressional action (P.L. 95-217, Section 208 (j)) this program should be very important in implementing the best management practices for salinity control as part of a cooperative effort among federal-state-local interests in alleviating water quality degradation from agriculture.

Most western states have revolving funds or low interest loan programs for water resources planning and development. Generally, these programs require that the applicant be an irrigation district or other corporate body. Where such state programs exist, legislation and/or regulations for participation qualification should be changed to allow: (a) individual irrigators to qualify; (b) a broader use of funds to include on-farm improvement practices, as well as improvement of delivery systems; and (c) the inclusion of program objectives to specifically improve water quality. When states have no such programs, a low or no-interest loan program containing the three components above should be adopted in order to cooperatively assist the federal government and local water users in achieving improved water management practices.

Dissemination of information about other state and federal agency incentive programs should be carried out by state water agencies. Emphasis should be directed to irrigated areas identified as producing salinity problems. Cooperation must be extended to ensure utilization of such programs.

By providing incentives for water users in designated salinity problem areas, farmers will have an opportunity to voluntarily improve their water use practices, which in turn will result in improved quality of irrigation return flows. This is consistent with the philosophy of encouraging voluntary compliance versus forced or involuntary compliance. If states are to create standards and criteria for beneficial use, some mechanism should be made available to the farmers that will facilitate compliance with the new criteria. Without it, irrigators have legal grounds to continue exercising their water rights as they have in the past. The legal cost to the state and water users in litigation to change their traditional practices may be much more expensive than devising procedures that increase the efficiency of water use, while still protecting downstream users.

Development of a Water Market

Irrigation water supplies are allocated among farmers on the basis of the rights they established in the past. Thus, allocation of water is based on legal rather than economic grounds. Because of this, users tend to apply or at least divert all the water to which they are entitled throughout the irrigation season, even though it is not needed by the crops. Salinity problems in irrigated agriculture are largely the result of excessive irrigation return flows, which in turn are attributable to water allocations and applications being much greater than crop water requirements. In these same cases, the farmer pays only for the conveyance cost of the water which is too low to encourage efficient use. The price of water is a poor reflection of the "opportunity cost" or the value of the water with respect to alternative uses. One alternative is a water market where water could be sold, traded, or rented which would reflect these opportunity costs.

The establishment of a water market would alter the present institutional arrangement. From a practical standpoint, it would seem desirable to alter that arrangement as little as possible to assure its acceptance. To minimize the disruption to the present institutional arrangements for allocating irrigation water, a water rental market could be established. Under such an arrangement, the present structure of water rights and allotments would be maintained, but would permit rental of surplus water to other users in the irrigated area, or upstream, without jeopardizing these rights and allotments.

There is a legal requirement that water transfers not injure other water rights. In most cases, transfers must be restricted to the amount previously consumptively used by the crops; however, the question of whether or not reduced diversion requirements can be transferred to other locations is dependent upon whether other water rights are affected as a result. Irrigation return flows from many irrigated areas are already part or all of the water rights of downstream users. In most western states under the existing laws, the water surpluses should go to "junior" appropriators. A water rental would have to address these problems and, in some cases, the "junior" rights would have priority. The ability to initiate a water market, particularly for transferring water outside the irrigated area, becomes "site specific."

An impediment of water rights is the transfer restriction of rights within an irrigation system to other uses, or out of the basin. This constraint may exist in the substantive water law or as a result of the organizational and administrative system of the state. Only a few states prevent the sale and transfer of water rights for other uses. States restricting transfers rely upon the appurtenancy concept to prevent such transfers. The law should be modified to reflect state encouragement in the renting, leasing, transferring or selling of water rights to other uses and places so long as the vested rights of others are protected. For example, although there are no restrictions on the transfer of water rights in Colorado, the organizational red tape--delay and expense--acts as an impediment. Changes in the administrative and judicial system should be made to facilitate exchanges of water rights. Recognition of water right exchanges and a change in the concept of beneficial use to include recreation, aesthetics, fish and wildlife, and other beneficial uses would serve to nullify the fear of losing that portion of the water right not exercised by permitting the transfer of unneeded portions to other uses within the system.

Removing rigidities in the law to give the water right holder greater freedom and flexibility will eliminate many of the irrigation water quality problems perpetuated by the appropriation doctrine. A legal solution would be to merge the economic benefits from a more liberal transfer policy into legal guidelines that still provide protection to existing water rights holders. This would require the adoption of an incentive mechanism to encourage water users to "market transfer" some of their water through the irrigation companies. Water could be rented or leased to upstream water users or for new water demands, with the revenues used to improve the irrigation system.

A substantial change in water laws affecting the administrative organization of the state should be enacted to enable greater cooperation between the state agency and water users. At the same time, changes in the water laws should permit the state to concentrate on development of a desirable state water plan while specifically enacting legislation that permits state water resources agencies or other public organizations to acquire water through appropriation, purchase, abandonment, or condemnation. This type of legislation will grant the state greater freedom in carrying out its responsibilities and negotiating agreements with its water users and other states.

There is a need for a means of allocating and reallocating water within the irrigation system by an organization cognizant of the needs of water users within the system, the state water development plan, the basin and international impacts. The development of a centralized state brokerage system is a possibility that would be operated as a market center for the exchange and sale of water rights, or renting of water available under the rights held (Radosevich, 1972). This brokerage system could be organized as a public or private institution. Water users would be permitted to divert only that amount of water necessary for their operation, without fear of losing the unused decreed quantity, and lease or rent the difference to other users. Hence, there would be an economic incentive to implement more efficient irrigation water management practices in an attempt to reduce the quantity of water applied.

A brokerage system created as a public entity could be established in the Office of the State Engineer or Water Planning and Resource Department. These offices, or their respective divisional offices located throughout the state, would list all available water for rent, lease, exchange, or sale. The location of available waters would determine the impact upon other vested rights, but the responsibility for delivery and protection of such rights would rest upon either the water right holder or water acquirer. Uniform prices for units of water could be established, or the available water could be marketed to the highest bidder. The adoption of such a system in state organizations would require changes in agency law. Likewise, it would be imperative that the state should have the power to purchase, condemn, or receive water rights. This would allow the state to take action against appropriators who refuse to implement efficient practices. The state should have the power to acquire their unused rights and retain them for future use while renting or leasing water during the interim. A percent of the transacted price would be retained for the operation and maintenance expense of the brokerage system (Radosevich, 1972).

ORGANIZING FOR IMPLEMENTATION

Local Entity

Based upon monitoring and analysis for identifying significant irrigation return flow salinity problem areas within the state, the state water pollution agency should: (a) designate the boundaries of the problem area, which may be the boundaries of an irrigation system, or subsystem, or watershed; (b) designate an entity that is a legally constituted body representing water users within the area to undertake responsibility for working with the water users, collecting data, and disseminating information; and (c) ensure that the local entity is carrying out the best management practices developed for the area.

From a practical point of view, this entity may be a newly formed organization, an existing organization such as the irrigation district that assumes the program, or a federation of several existing organizations. The area entity would utilize a representative board of commissioners that would be responsible for carrying out monitoring, discussing with water users ways to alleviate unreasonable salinity degradation by irrigation return flows, and encouraging voluntary improvement of irrigation practices by those users identified as contributing to the area's problems. For those users who refuse or fail to respond as recommended, entities representing users within an area would notify the state water quality control agency of the specific noncompliance. The state would proceed under existing federal and state law to initiate control and enforcement action under the general provisions of the water pollution laws prohibiting discharges of pollutants and violation of stream standards. The area entity is thus responsible for assisting in managing the agricultural practices within the designated area, but control and necessary enforcement are appropriately left to the state.

Water User Organizations

A crucial element in implementation of an effective salinity control program is gaining participation of the users. The basic unit of organization should be at the lateral subsystem level because it is a natural hydrologic subunit where farmers know each other and interact on a daily basis. In some irrigated areas, the jurisdiction of the irrigation companies or districts does not include the laterals; so an organizational vacuum for water users on these laterals results. In other cases, the irrigation companies are also responsible for the operation and maintenance of the laterals; so there are no real organizational problems with the individual farmers along each lateral.

The goal should be to gain participation by all water users on each lateral. This may not always be possible due to human problems. While the organization could be on an *ad hoc* or informal basis, experience indicates that it is probably best to aim for a formal organization with rules developed by the members. A formal organization with its own rules and regulations also makes it easier for the implementing agency because all parties have a knowledge of the structure and mechanisms involved. When leadership is defined, this facilitates the work of the implementing agencies.

Water users usually have been formally organized as nonprofit mutual irrigation companies under their particular state laws. If each lateral must also be formally organized, members of these associations may encounter problems with lawyer fees for incorporation. This can be partially overcome by providing example sets of bylaws and other provisions to farmers considering organization. In fact, alternative examples can be provided to farmers to help decide whether the set of rules and regulations meet their special needs for the most effective means of operation and maintenance of their particular water delivery and irrigation systems. These examples could be described and illustrated in a manual or booklet and made available to interested farmers. The booklet should explain the benefits of formal organization, how to organize legally, and the types of bylaws and provisions required. It is important that such a booklet be well illustrated and in easily understood language, rather than containing much legal jargon which is not easily understood.

Technical Assistance

The most likely candidate for providing the necessary technical assistance to implement the best management practices for salinity control is the Soil Conservation Service. The Soil Conservation Service has the responsibility for this area, with cost sharing funds provided by Congress to the United States Department of Agriculture for alleviating water quality degradation from agriculture. At the same time, there are state programs that can also provide funding and technical assistance personnel. The cooperation and coordination of state and federal technical assistance, including the Cooperative Extension Service, is highly desirable.

TRAINING

Training Field Personnel

The primary agency providing technical assistance to farmers for a salinity control program will likely be the Soil Conservation Service. The Soil Conservation Service would cooperate with other state agencies in supplying the required technical assistance. Given the levels of manpower needed to work with farmers and the current shortage of trained manpower with on-farm water management experience, special short courses for training personnel would be essential. As a complement to technical competence, personnel working directly with farmers should know how to develop good working relationships with their clients. Additionally, personnel should have definite skills and knowledge related to organizing farmers into water user associations for action programs. Personnel must also have the capabilities required for assisting farmers in increasing the efficiency of existing irrigation practices and maintaining and improving conveyance systems.

Technical assistance to farmers include convincing them to use "scientific" irrigation scheduling procedures and other improved irrigation practices. The focus on improved irrigation scheduling is essential because the existing piece-meal methods of scheduling are inadequate as an individual salinity control measure.

Farmer Training Materials

Materials are needed to motivate farmers and help them understand the importance of improving present water management practices for increased crop production and control of salinity. Data obtained in problem identification and alternative solutions should be utilized in preparing well-illustrated materials for farmers. These materials should graphically and clearly define the problem, explain its consequences, document the contributing factors, and explain the costs and benefits. Alternative solutions should be carefully delineated and estimated costs presented.

Techniques for such communications could include slide presentations, a condensed booklet, and selective use of local electronic media. Since a comprehensive salinity control program requires changes in attitudes and behavior, the first major consideration should be the establishment of definite communication objectives. To make the program successful in reaching all water users and the community, several complementary communication methods should be continuously used to reinforce the central messages. Local print and electronic media must be identified, enlisted, and used efficiently and creatively to attain optimum results. Essentially, salinity control is a problem of water conservation which requires much communication directed to farmers and communities.

FARMER ACTIVITIES

Farmer Participation

One of the unique characteristics of improving on-farm water management is that the degree of success is highly dependent upon the degree of participation of each individual farmer, as well as their ability to cooperate collectively for the good of all water users. The construction of on-farm physical improvements only provides an increased potential for water use efficiency, whereas the success achieved is dependent upon the operation, management, and maintenance of the physical improvements. This, in turn, is dependent upon the level and ability of technical assistance provided, farmer attitudes, and the degree of credibility between all individuals involved.

Credibility and acceptance by the farmers begins when the basic training and motivational materials are initially used to describe the problem. Efforts to organize the water users provide an opportune time to develop early rapport with the farmers. Credibility and acceptance of the technical personnel by farmers during the planning and implementation of individual farm plans for improved water management is essential to the long-range goals of a control program. Credibility and good communication must exist during the collective negotiations in determining the physical improvements to be made. Farmer participation is crucial during these stages in order that a plan of development evolves that is acceptable to the water users and also satisfies the goals of the salinity control program.

The final step in this process dictates the real success of the entire program. After spending vast sums of money to construct physical improvements, the test of effectiveness centers largely around the operation, management, and maintenance of these improvements. This is the phase of the work where the rapport developed with the farmers pays high dividends. Unfortunately, this step is very time-consuming and most frequently neglected. Considerable evaluation is required to perfect or maximize these new improvements so they operate at their full potential. This is the key to the success of any nonpoint source pollution program.

Farmer Recognition

Many experiences have demonstrated the importance of farmer recognition. Farmers usually can sell a program to other farmers more successfully than public officials. Where possible, farmers should be given special recognition because the success of any salinity control program ultimately rests with the degree of participation by farmers themselves. Several methods employing farmer recognition can be effectively utilized to motivate other farmers. Proper use of radio and television announcements and newspaper articles can help considerably in fostering enthusiasm for the program. Local newspapers are usually willing to provide coverage on news related to natural resources and agriculture. Local television and radio stations can often be expected to cooperate with the project by disseminating news related to the salinity control activities.

In addition to reports about current activities of the salinity program, the news media are also interested in covering human interest stories. If human interest reports and farmers' testimonials are well prepared, they can excite other farmers about the program. Such publicity is free and probably can generate better image-building for the state and federal agencies than these agencies do for themselves.

Awards should be considered for those farmers who have made exceptional progress in improving their on-farm water management practices. Awards for providing leadership in the local water user organization(s) should also be considered. Awards presented to each water user served by the lateral demonstrating the most efficient use of water would be highly effective in promoting the goals of an improvement program. These awards would serve to: (a) make farmers more aware of improved management practices; (b) foster efficient irrigation practices; and (c) promote cooperation to help each other improve methods. News media coverage of such awards also provides additional incentives for improved water management on the part of other farmers. Framed photographs of farmers engaged in improvement activities with an inscription could be considered for presentation. Plaques could be presented to cooperators to show appreciation for their contributions.

An excellent method of employing farmers for promoting wide interest in a project , once substantial progress has been made in an improvement program, is the use of Field Days. A Field Day could be held annually that would involve strong participation by local farmers. Water users and irrigation company leadership from nearby areas could be given special invitations to attend the Field Day in order to observe firsthand the implementation of a salinity control program. In addition, special tours could be arranged during other times of the year for a group of irrigators from any particular area to visit the project area and meet with farmers who have participated in the program. The emphasis should be farmer-to-farmer interaction, with the local farmers being highlighted rather than technical assistance personnel. These personnel, however, should play a strong backstage role in facilitating this interaction.

MONITORING, EVALUATION, AND REFINEMENT

A monitoring network should be established so that the impact of the implementation program can be measured. A part of this network would be the stations used in the inflow-outflow analysis. In addition, some of the groundwater monitoring stations used in developing the hydro-salinity model would be incorporated into the monitoring network, along with some new stations scattered throughout the irrigated lands near the river or point(s) of outflow.

Evaluation research techniques are available which, if properly utilized, can be used to determine the strengths and weaknesses of project implementation. Information from such studies is needed by sponsoring and implementing agencies to discover the most effective and efficient methods of working cooperatively with farmers. Continual and periodic evaluation mechanisms are needed in order to continually refine the implementation program. Feedback is needed both from farmers and technical assistance personnel for improving: (a) the delivery of the salinity control technological package; (b) the operation and management of the physical improvements; and (c) the cost-effectiveness of the entire program. Credibility with the farmers will be strengthened by continually refining and improving the implementation program.

Extension communication strategies should be designed into the project work plans so that various techniques can be effectively evaluated. While technical expertise for such programs is usually adequate, there is a general weakness in designing and evaluating extension communication strategies. Technical assistance personnel should be given short courses in skills needed for working effectively with farmers. As stated often in this report, the key variable in achieving successful program implementation and long-term effective management of improved systems are the farmer clients themselves. Consequently, communication techniques used for working with farmers as individuals and groups should be designed into the implementation program and evaluated to the same degree as the technical components and activities.

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APPENDIX A

DESCRIPTION OF SELECTED IRRIGATION RETURN FLOW MODELS

FORMAT OF DESCRIPTIONS

The models that might be employed in salinity control planning were referenced in Section 6. This appendix contains a brief technical review of these models developed by Walker (1978b). The format of the descriptions is divided into the following input segments:

(1) Model grouping;
(2) Descriptive or developmental references;
(3) Scope of the model;
(4) Input requirements;
(5) Spatial and time scales;
(6) Structure of the code;
(7) Basic mathematical or analytical approach; and
(8) General comments.

In describing various models, as much as possible of the information presented originates in the cited references in order that descriptive errors are minimized. The phrases used in describing various aspects of a model are intended to alert the reader's own understanding rather than trying to be exhaustive in detail. Those unfamiliar with a modeling area are encouraged to obtain and review the reference material for a more in-depth assessment.

Model Scope

Under the heading of model scope, a few sentences are given to describe what the model simulates and its expected output, including the use of input dumps, error flags, and intermediate calculation results to make the model more useable. Most models print input data to insure that it has been input properly. Error flags and results of intermediate computations are not generally included.

Input Requirements

A list of control parameters and basic input data is included to identify to the potential user the information required to utilize the models effectively. This list is not exhaustive, but represents input data of most importance. Occasionally, a series of data is described in more general terms or classified in order to reduce the length of the descriptions.

Spatial and Time Scales

It is important that the "size" of the modeled portion be identified in comparison to the problem's real dimensions. The interval or time scale is also useful in selecting a model to evaluate an IRF problem since detail of the study is directly related to time resolution. The dimension of the simulation may also be provided in this section, thereby indicating the assumptions made about the system's structure.

Computer Code Structure

In these sections, the programming language, core requirements, expected execution times, internal program linkage, and application comments are made. Computer words have different byte lengths and execution times depending on whether or not program compilation is necessary. A major problem occurs when the code is written in the CSMP format for IBM computers because much of the program then becomes part of the basic computer software and storage-time requirements are not known.

Basic Mathematical Approach

It is difficult to express in one or two paragraphs what a complex simulation model accomplished and in what manner. Key phrases and words are used as much as possible to convey to the reader a great deal more than is actually written, and if possible these phrases were taken from the documentation of the code or reference material. The assumptions in a model are at least partially apparent to the already informed reader from the description of what is calculated. Often classical equations in the literature are named without reference. These are noted in the text and generally identify the analytical approach taken.

General

Of general interest to modelers is where the model can be obtained, verification that has occurred, the stage of development and future applications, and special problems that might be encountered in its use. For the most part, this section contains comments on verification and acquisition.

MODEL DESCRIPTIONS

The individual model descriptions are given in the following pages.

MODEL: A-1

REFERENCES:

Bureau of Reclamation. 1977. Prediction of mineral quality of irrigation return flow, Volume III, Simulation model of conjunctive use and water quality for a river system or basin. User's Manual. EPA-600/2-77-179c. Robert S. Kerr Environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Ada, Oklahoma. August. 295 pp.

MODEL SCOPE:

Simulation is of the water and salinity impacts in a river basin resulting from urban, industrial, and agricultural water uses. Formulated as part of a need for evaluating irrigation return flows in a river system, the model is primarily oriented to this end. In addition to the mass balance of surface and groundwater in a river section, the model simulates reservoir operations, and a comparatively complex analysis of the soil salinity system. Program features both input dumps and error flags. Intermediate results are not presented.

INPUT REQUIREMENTS:

Control parameters are initially read in to completely dictate problem structures since enough flexibility has been added to allow simulation of river systems with a multitude of local conditions. Control parameters include division of system into segments (nodes), processes being simulated in each segment, node structure and labels, and time dimensions. Input data descriptive of local hydrochemical processes are input as follows: (1) aquifer volume and salinity; (2) reservoir conditions and operating rules; (3) sediment analyses; (4) irrigated soil chemical and hydraulic characteristics; (5) hydropower generation parameters; (6) discharge and chemistry of major surface and subsurface inflows; (7) demands by agricultural, municipal and industrial users; and (8) allocation of flows within an irrigation system.

SPATIAL AND TIME SCALES:

Simulation is of hydrochemical systems on a river basin scale or segment thereof. Time period utilized is one month at minimum scale to several years duration of simulation.

COMPUTER CODE STRUCTURE:

Internal program linkage is accomplished by subroutines and functions with both common and call statement data transfer (control parameters are generally passed in the call). Code is set up to read and write results as output or onto tape or disk systems. Approximate core and execution time requirements are 140 k bytes and 120 central processor seconds, respectively. Program language is Fortran.

BASIC MATHEMATICAL APPROACH:

The program utilizes an iterative scheme for balancing mass between "nodes" or subbasins comprising the area being analyzed. This model includes substantial simulation of reservoir and stream management. After initialization of the system, the various demands are compared with the available stream flow to determine if a shortage is occurring. If insufficient water is available in the river, a series of reservoir checks and manipulations are made to adjust flow if possible. Return flow volumes and chemistry are then computed and checked against initial assumptions. Iterations are repeated until mass balance is achieved.

Of particular interest in this review are the model segments describing the irrigation return flow system. Diversions are determined by computing the consumptive use (using the Penman equation) and then dividing by conveyance and farm irrigation efficiencies. Return flow is then the difference between demand and consumptive use. The chemical simulation of the soil profile is based on a simplified version of the model presented by Dutt, et al., 1972.

GENERAL:

Model is very complex in scope and therefore difficult to apply without some previous experience in hydrosalinity modeling on a large scale. However, the user manuals are excellent descriptions of the computer system and can be used to implement the model. This model has been used extensively by the Bureau of Reclamation in studies throughout the western United States. The code is available from the Bureau of Reclamation.

MODEL: A-2

REFERENCES:

Crawford, N. H. and A. S. Donigian. 1973. Pesticide transport and runoff model for agricultural lands. EPA-660/2-74-013, Office of Research and Development, U.S. Environmental Protection Agency, Washington, D.C. December. 317 pp.

Donigan, A.S. and N.H. Crawford. 1976. Modeling pesticides and nutrients on agricultural lands. EPA-600/2-76-043. Office of Research and Development, Environmental Research Laboratory, U.S. Environmental Protection Agency, Athens, Georgia. February. 211 pp.

MODEL SCOPE:

Simulation is of runoff, snow accumulations and melt, sediment loss, pesticide-soil interactions, and soil nutrient transformations. Analysis involves transport of pollutants from both surface and subsurface sources. The model is intended for watersheds up to two square miles in which in-channel processes and transformations can be neglected. Parameters simulated include mass transport of water, sediment, pesticides, nitrogen and phosphorus. The program is set up to operate in either a calibration or production mode. In general, the output includes water movements (runoff, infiltration, evapotranspiration, and storage), sediment transport, pesticide transport and transformation in various soil layers and in sediment, nutrient transformations in the soil profile, and leaching of nitrate. The only salinity parameter in this version of the model is chloride. Output can be controlled to intervals from every 5-15 minutes in the simulation to monthly summaries.

INPUT REQUIREMENTS:

Data necessary to operate the model can be divided into control, hydrologic, snow, sediment, pesticides, and nitrogen-phosphorus parameters. The control parameters include type of run, units, output interval, snow, pesticide, nutrient simulation options, input data checks, time intervals for calculations, watershed structure, and time limits. For the hydrology submodel, input includes soil moisture storage (capacity and initial), length, slope, roughness, intake, evaporation coefficients, and surface storage of watershed, groundwater return flow timing, and groundwater distribution and conditions. The snow accumulation-melt analysis requires a number of coefficients describing the energy balance description of the solid-liquid phase transformations, climatological parameters (radiation, temperature, wind), and topographic description of the watershed. To compute the sediment phases of the model, the user must supply crop cover, tillage effects (depth, timing, and fine deposits), soil depths and bulk densities, rainfall splash coefficients, overland flow exponent and wash-off coefficient, and the initial soil fines deposit. Pesticides are described using application timing, solubility, fixing capacity, coefficients in the Freundlich adsorption/desorption equation, decay rate, and control coefficients noting how the pesticide is applied and whether or not a single-valued adsorption/desorption algorithm is to be used. Nitrogen and phosphorous simulation begins by first specifying time steps, number of fertilizer applications, and harvest dates. Then a series of nitrogen reaction rates for mineralization, immobilization, nitrification, denitrification, and uptake are input. Similar coefficients are needed for phosphorous analysis. Storage of nitrogen (in its various forms) and phosphorus is detailed by describing the adsorbed, dissolved, absorbed, and gaseous phases.

SPATIAL AND TIME SCALES:

Calculations are based on a 5 or 15 minute real time interval with results lumped in hourly, daily or monthly summaries. The spatial scale is of a 1-2 square mile agricultural watershed.

COMPUTER CODE STRUCTURE:

The basic code structure is one of a main program controlling the order and presentation of input, calculations, and output with subroutines encompassing specific submodel tasks. The code is written in Fortran IV and run on an IBM 360/67 computer but appears readily adaptable to other machines. The code is very lengthy and is best operated in compilation and production steps. The number of pages of output can be several hundred with even routine analysis. Neither core requirements nor execution times are noted, however, both are comparatively large on visual inspection.

BASIC MATHEMATICAL APPROACH:

This model is too large for a thorough description of the mathematical approach. Consequently, only a brief summary will be presented here with more detail left to the interested user. The code involves six primary subprograms: (1) MAIN which orders overall execution; (2) LANDS which simulates the hydrology and snow; (3) SEDT, the analysis of sediment, (4) ADSRB, the pesticide adsorption and removal program; (5) DEGRAD, pesticide degradation; and (6) NUTRNT, which is the simulation of nutrient transformation and removal.

The LANDS subprogram is derived from the Stanford Watershed Model presented in various publications. The hydrologic response of a watershed to inputs of precipitation and evaporation involves a water budgeting procedure which accounts for evapotranspiration, surface storage and retardance, infiltration, groundwater storage depletion and return flow, and overland flow.

The SEDT subprogram is a simulation of sheet and rill erosion involving the processes of particle detachment by rain drop impact and transport by overland flow. The particles detached during an interval are expressed as a power function of vegetal cover, precipitation, and a detachment coefficient. Overland transport is expressed as a power function of the detachment coefficient, initial volume of soil fines, and overland flow rate. Attempts have been made to include the effects of tillage operations by allowing the user to redefine initial volumes of detachable soil fines. Vegetal cover effects are specified monthly by the user with linear interpolation during the month.

The subprogram ADSRB is based on two alternatives. First, the standard single-valued Freundlich adsorption/desorption isotherm is used to separate adsorbed and dissolved pesticide concentrations. The second approach involves a multiple valued adsorption/desorption process taken from the work of Davidson, et al. (1975) reported elsewhere in this writing.

The degradation and volatilization of pesticides are simulated in the subprogram DEGRAD. Volatilization is ignored in the model's present version and degradation is assumed to follow a first-order decay function.

The nutrient simulation model (NUTRNT) attempts to predict nitrogen and phosphorous losses due to erosion, surface washoff, leaching, and biological conversion. Phosphorus is assumed to exist as organic phosphorus, solid phosphate, dissolved phosphates, and phosphorus adsorbed by the plants. Transformations are all based on first-order kinetics (temperature dependent). Nitrogen processes (mineralization, immobilization, nitrification, denitrification, and uptake) are based on first-order kinetics using literature values of the coefficients. Ammonium adsorption/desorption is also included in the model. Solution of the coupled differential equations is accomplished with a simple Euler integration scheme.

GENERAL:

This model is currently being improved and modified for a more general use. The nutrient phases remain unverified at this time although the surface hydrology and pesticide portions are tested against actual field data. Code listing is presented in the reference.

MODEL: A-3

REFERENCES:

DeWit, C. T. and H. Van Keulen. 1975. Simulation of transport processes in soils. Centre for Agricultural Publishing and Documentation. Wageningen, The Netherlands. 100 pp.

MODEL SCOPE:

The movement of heat, salts and ions, and water in unsaturated soil is described by a series of CSMP coded computer routines. Transport of these materials and energy encompasses diffusion, dispersion, and mass flow. The soil profile is divided into a series of compartments in which a sequential materials balance is computed. A number of the processes are not mutually exclusive, and the writers do not attempt to present a clear description for integrating the system together. Output includes the time and spatial distribution of the parameters. Plotting functions are also described.

INPUT REQUIREMENTS:

1. Soil heat flow: surface temperature fluctuations with time, thickness and number of soil depth increments, thermal conductivity of the soil compartments, and volumetric heat capacities; 2. Salt transport: initial moisture contents, labyrinth factors, initial solute concentrations, inflow volume and concentration, compartment thicknesses, a dispersion factor, and water diffusion coefficients; 3. Ionic diffusion: compartment thickness, diffusion distance, total depth, water contents, labyrinth factor, valency and initial concentrations of the ion under study, and diffusion coefficients; 4. Ionic transport: initial moisture contents, labyrinth factor, compartment geometry, dispersion factor, exchange capacities, water inflow, diffusion coefficients, solution-adsorption site equilibrium constant, and initial distribution of ions in the soil profile; 5. Infiltration: initial moisture contents, compartment geometries, initial water content at the soil surface, hydraulic conductivity and diffusivity functions of water contents.

SPATIAL AND TIME SCALES:

Calculation proceeds in time increments on the order of five to ten minutes and continues through periods of days. The analysis is limited to the 1-3 meter unsaturated zone and is one-dimensional.

COMPUTER CODE STRUCTURE:

Code is written in CSMP with Fortran output. Program is dispersed in the reference and not presented in a single listing. In addition, the five segments noted are not described as an integrated model; although, as will be pointed out next, the basic model structure is the same for each segment. Neither core nor execution times are available.

BASIC MATHEMATICAL APPROACH:

The soil depth is divided into a number of layers or compartments. With this geometry established and the initial conditions defined, the approach is to compute the movements from one compartment to the next based on the gradient between layers, and diffusion and dispersion functions.

In the heat flow submodel, the heat flow rate equals the temperature gradient between compartments multiplied by the thermal conductivity of the soil. The heat energy in a layer equals the temperature multiplied by the volumetric heat capacity multiplied by the compartment size. In order to calculate the heat flow with time, a time distributed surface temperature is defined along with the initial thermal characteristics of each compartment. The dynamic nature of the system does not allow for a direct equilibrium solution describing the heat status at each level in the soil. The procedure utilized is a centralized, forward integration procedure (explicit). At any instant in time the heat contents of all compartments are initially given. From this information the flow rates into and out of each compartment are computed and the volumetric heat contents are iteratively reviewed. The analysis can be for layered soils if their thermal coefficients can be defined.

The salt transport submodel operates in the same manner as the heat flow submodel except that flow is input at the surface (rate) with salt movement between compartments based on concentration differences (diffusion) and mass transport with the flow. Mass balance between compartments is maintained by recomputing salt accumulations. Dispersion due to tortuosity is also related with a coefficient to the concentration gradients.

Ionic diffusion in the absence of moisture flow is also based on the preceding approach with gradients based on ionic concentrations. The ionic transport submodel includes not only ionic diffusion, dispersion, and mass flow but cation exchange as well. Again, the ionic composition of each compartment is iteratively determined in conjunction with the net inflow or outflow as was described for the heat flow submodel. The added complexity of the monovalent-divalent ionic adsorption processes is handled by relating the adsorbed ions proportionally to the moisture content and exchange capacity and then distributing the relative composition of the adsorbed ion in an equilibrium constant approach.

In the heat and solute movement submodels, the conductivity and diffusion-dispersion coefficients were not dependent on the relative concentration of the parameter being simulated. In the case of infiltration, however, diffusivity and hydraulic conductivity are moisture dependent. To simulate the moisture movement between compartments, an "average" moisture content is determined for the gradient information. In this submodel the average is actually a weighted average to take into account the nonlinear diffusivity-hydraulic conductivity versus moisture content relationships. The flow between layers is thus the average diffusivity times the moisture content gradient plus the average hydraulic conductivity. The overall procedure is to first establish the initial and boundary (inflow) conditions. Then diffusivity and conductivity are calculated for each layer yielding the interlayer moisture movement. Net moisture content change and the input water are routed through the compartments by successively computing-adjusting until a stable mass balance is achieved or until changes from iteration to iteration are small.

GENERAL:

Although the model is detailed in the reference, a potential user is still left with a considerable effort to integrate the parts into a useable program. Fortran users will be able to develop such models with about as much effort.

MODEL: A-4

REFERENCES:

Frissel, M. J. and P. Reiniger. 1974. Simulation of accumulation and leaching in soils. Centre for Agricultural Publishing and Documentation, Wageningen, The Netherlands. pp. 70-84.

MODEL SCOPE:

Simulation is of diffusion, dispersion, adsorption-desorption, mass transport, and volatilization of herbicides in a homogeneous soil profile. Output includes the time and spatial distribution of the herbicides in the soil system.

INPUT REQUIREMENTS:

Two options are available: (1) instantaneous equilibrium (no adsorption); and (2) noninstantaneous equilibrium (adsorption-desorption). Both model options require volumetric moisture contents, bulk density, gas and liquid phase fractions, distribution ratios (soil/water, water/gas), soil profile depth, diffusion coefficient for gaseous phase, surface flux and concentration, and first-order decomposition rate coefficients for the herbicides. The noninstantaneous option also requires adsorption-desorption rates and water system diffusion rates.

SPATIAL AND TIME SCALES:

Simulation is of one-dimensional analysis of a one meter unsaturated soil profile. Calculations are presented at intervals specified by the user in hours or days.

COMPUTER CODE STRUCTURE:

CSMP

BASIC MATHEMATICAL APPROACH:

The flux of the herbicides due to water movement is described basically by the compartment modeling approach noted in other CSMP models. For the instantaneous equilibrium model, herbicides migrate in both the water and gaseous phases (only diffusion flux for the gaseous phase). Decomposition of the herbicide is a first-order reaction based on a decay rate. The analysis describes the convection and diffusion flux in the water phase and the diffusion flux in the gaseous phase. In the noninstantaneous equilibrium model, a linear adsorption reaction is assumed and added to the instantaneous equilibrium approach.

GENERAL:

The mathematics for the herbicide models are well defined in the reference. The models are listed in the reference. Field verification is not reported.

MODEL: A-5

REFERENCES:

Frissel, M. J. and P. Reiniger. 1974. Simulation of accumulation and leaching in soils. Centre for Agricultural Publishing and Documentation, Wageningen, The Netherlands. pp. 54-69.

MODEL SCOPE:

Simulation of diffusion, dispersion, and mass transport of Na^+, K^+, Ca^{++}, and Mg^{++} in soils. Model considers nonlinear adsorption-desorption. Output includes the time and spatial distribution of the salinity cations in the soil solute, adsorbed phase, and in deep percolation. The soil is considered homogeneous.

INPUT REQUIREMENTS:

Input consists of depth distributed and exchangeable solution Na^+, K^+, Mg^{++}, Ca^{++}, moisture content, Na^+/K^+, Ca^{++}/Mg^{++}, and adsorbed cation fraction/ cation exchange capacity ratios, inflow rates and concentrations, fixed K^+ and fixation and release rates.

SPATIAL AND TIME SCALES:

Spatial scale is a one-dimensional analysis of a one meter or so depth of unsaturated soil. Calculations are reported in hours.

COMPUTER CODE STRUCTURE:

CSMP

BASIC MATHEMATICAL APPROACH:

The diffusion, dispersion, and mass transport are simulated by the CSMP compartmental model described previously. In addition, the cation exchange and potassium fixation are included to adjust the transport results. The exchange reaction is assumed to occur instantaneously. A Gapon equation, along with nonlinear functions (Vanselow), are incorporated, but the principal approach is one developed by the authors. Potassium fixation is a first-order reaction depending on relative concentration in solution and on the soil.

GENERAL:

More detail concerning the exchange processes is left to the interested reader. The input can be time distributed, but it is not clear how the moisture is redistributed since moisture content-conductivity relationships are not included. Program is listed in the cited reference.

MODEL: A-6

REFERENCES:

Frissel, M. J. and P. Reiniger. 1974. Simulation of accumulation and leaching in soils. Centre for Agricultural Publishing and Documentation, Wageningen, The Netherlands. pp. 12-20.

MODEL SCOPE:

Simulation of diffusion, dispersion, and mass transport of completely soluble compounds in the soil solute. Output includes the time and spatial distribution of the solute concentration and deep percolation. The soil is considered homogeneous.

INPUT REQUIREMENTS:

Input to the model includes depth of soil profile, number of compartmenta soil layers, surface flux and inflow concentration, diffusion constant, anion exclusion ratio, initial moisture content, tortuosity and dispersion coefficients with soil depth, output frequency, and initial distribution of solutes.

SPATIAL AND TIME SCALE:

The spatial scale is an approximately one meter, one-dimensional view of an unsaturated soil profile. Calculation times are on the order of minutes with output printed at selected aggregate intervals of hours.

COMPUTER CODE STRUCTURE:

CSMP

BASIC MATHEMATICAL APPROACH:

The soil profile is divided into 40 compartments or layers with initial conditions defined in each layer. The diffusion coefficient for the boundary between two layers is computed using mean values of moisture content, tortuosity, and dispersion values. Diffusion rates are based on Fick's Law which calculates an average concentration gradient between layers and multiplies it by the diffusion coefficient to arrive at the flow. Mass flow is also based on average concentration and moisture flow rates. In this model, water flux is based on a steady-state infiltration.

The basic mathematical approach involves first calculating the movement rates between compartments. The rate of change in compartmental solute concentration is then computed and integrated using a standard CSMP semi-parallel method such as a fourth order Runge-Kutta method. The rates are recomputed and the iteration repeated until the compartment concentrations have stabilized.

GENERAL:

The program is set up for tritiated water. For other anions (Cl^-, NO_3^-), the rates are multiplied by the exclusion ratio. Code is presented in the cited reference. Verification is not reported.

MODEL: A-7

REFERENCES:

Gupta, S.K., K.K. Tanji, D.R. Nielsen, J.W. Biggar, S.C. Simmons, and J.L. MacIntyre. 1977. Field simulation of soil-water movement with water extractions. Water Science and Engineering Paper 4013. University of California, Davis, California. May. 95 pp.

MODEL SCOPE:

Simulation of "infiltration, vertical seepage, and uptake by plants as related to the hydraulic properties of the soil, soil layering, the root growth characteristics of a given crop in a given soil profile, evapotranspiration rates, and frequency, rate, and amount of irrigation," is presented. Outputs, in addition to an input dump, include hourly values of moisture content, suction, and flux throughout the profile during an irrigation and daily values during nonirrigation periods. Daily mass balances are also given along with distributed totals for each run describing the irrigation input, evaporation and transpiration, and flux at each node. Data may be supplied by disk or cards.

INPUT REQUIREMENTS:

The program requires a number of control parameters to direct the calculations through the alternatives for various steps. First, boundary conditions when not calculated directly must be specified for field and crop conditions. The problem size and decomposition structure is defined next, i.e., distribution of nodes and material numbers above and below each node. Dates for planting and harvesting are also read in; then a series of flags are specified. Leaf-area-index options include direct input of LAI versus time, or a user specified distribution. Partitioning transpiration and evaporation from inputed values of potential evapotranspiration can be either computed with techniques using LAI related energy balance at the soil surface, or an option supplied by the user. Stress effects on transpiration include options for on-off, logarithmic decrease, linear decrease, a combination on-off and linear or a user supplied function. Soil profiles may be either homogeneous, nonhomogeneous, or layered, each of which requires the hydraulic conductivity-moisture content relationship (expressed as polynomials). Root growth options involving a negative exponential relationship, distributed density functions, or a user supplied system is specified and associated data read into the model. Moisture extracted by the rooting system is evaluated in a sink term added to the moisture flow equation. The form of the sink may be a macroscopic Nimah-Hanks type, related to soil suction, or supplied by the user. Associated data would then be necessary to define the pertinent coefficients. Finally, surface boundary conditions describing static, quasi-dynamic, dynamic, or semi-infinite depth must be known.

TIME AND SPATIAL SCALES:

During an irrigation, time increments may be as small as 0.1 to 1.0 hour with aggregated values presented daily. Spatial resolution is a one-dimensional analysis of the unsaturated region below an irrigated surface.

COMPUTER CODE STRUCTURE:

A main program-subroutine system with common and call information transfer constitutes the essential code structure. Code is written in Fortran IV. Execution time and core requirements are not specified in the reference, but neither are expected to be a problem at most computer facilities.

BASIC MATHEMATICAL APPROACH:

Water entering the soil via irrigation or precipitation either redistributes in the root-zone or evaporates from the soil surface. Knowing the potential evapotranspiration rate, surface evaporation is delineated by a leaf area index related radiant energy balance computation at the soil surface. The moisture not evaporating from the soil surface moves through the soil profile and/or is extracted by the rooting system.

Soil moisture movement in the root-zone is simulated with the single phase, time dependent solution to the Darcy equation. A sink term is added to the basic finite difference solutions to accomplish plant uptake. The model handles the sink term in an interesting way. An iterative solution of the K-θ system is undertaken until a mass balance between internodal flux and total transpiration is accomplished. A similar mass balance relating the moisture remaining after plant uptake with the distribution of moisture in the profile is utilized to iteratively change time resolutions until both estimates are congruent. Thus, the model automatically insures a mass balance by forcing the detached solutions to the flow equations to be in agreement.

GENERAL:

This model is the first phase of a comprehensive study aimed at simulating nitrogen behavior in soils. Verification has been made against very detailed field data, although only at one location. The code reflects a fair state-of-the-art description of the physical processes in the root zone even though more refined treatments of some segments are possible. However, the sophistication among these segments appears quite homogeneous. Although classified primarily as a research tool, the approach allows application to a number of field situations. Code is available from the authors cited above.

MODEL: A-8

REFERENCES:

Hill, R.W., E.K. Israelsen, and J.P. Riley, 1973. Computer simulation of the hydrology and salinity systems within the Bear River Basin. PRWG 104-1. Utah Water Research Laboratory, Utah State University, Logan, Utah. 122 pp.

Huber, A.L., E.K. Israelsen, R.W. Hill, and J.P. Riley, 1976. Basin simulation assessment model documentation and users manual. PRWG 201-1. Utah Water Research Laboratory, Utah State University, Logan, Utah. August. 30 pp.

Narasimhan, V.A., and E.K. Israelsen, 1975. A water-land use management model for the Sevier River Basin, phases I and II. Information Bulletin 24. Utah Water Research Laboratory, Utah State University, Logan, Utah. September. 44 pp.

MODEL SCOPE:

Simulation involves the basic hydrologic relationships in river basins and/or watersheds. The model incorporates relationships describing hydrologic processes which are linked together by the conservation of mass principle. Salinity is added to simulation by assuming the hydrologic processes change the chemical concentration in the system by storing, concentrating, diluting and/or picking up salts. Salinity related processes are specifically developed for irrigated soils and small storage reservoirs.

The model concept is one of inflow-outflow = change in storage. Inflows simulated include stream inflows, tributary inflow, precipitation, subsurface inflow, and imports. Outputs are surface and subsurface flows, evaporation and evapotranspiration, and exports. Internal system simulations consider canal and groundwater diversions, surface and subsurface irrigation return flow, and soil moisture groundwater systems. Reservoir operations are provided with a specific submodel.

Use of this model falls under two categories. First, given the necessary input data, the simulation of various hydro-salinity flows is compared with actual measured values in order to calibrate the model. A pattern-search optimization technique is utilized to systematically optimize the calibration. The second model use which is based on proper calibration is to test management alternatives (changes in cropping patterns, alternative reservoir operations, and improved irrigation practices) on the water quality of the system outflows.

INPUT DATA:

Control parameters allow user to select one of four input options: (1) read run data for reduction and handling internally; (2) read data directly to simulation system; (3) read data from computer memory; and (4) read parameter bounds for calibration process. Other control parameters set boundaries for calibration process. Input of a hydrologic nature which must be supplied includes monthly percentage of daylight hours, crop and phreatophyte consumptive use coefficients, canal diversion, land use acreages, precipitation, soil moisture characteristics, temperature, river inflow, tributary inflow, subsurface inflow, surface outflow, and reservoir operations. Salinity data are also necessary for the above noted water flows.

SPATIAL AND TIME SCALES:

Simulation is of single or multiple river system subbasins. Analysis is partially dynamic in nature although steady state is assumed within a time frame of 1 month. Time resolutions are monthly with multiple year analyses inherent. Model is two-dimensional in nature.

COMPUTER CODE STRUCTURE:

Internal program linkage is accomplished by subroutines with call and common data transfer. The program in its initial versions was written and utilized on a digital-electric analog hybrid computer at Utah State University. Hydrology is currently available in a digital format. The digital segments should be adaptable to other computer systems without much difficulty. Language is Fortran IV.

Execution time and memory requirements are not given. General examination indicates core requirements on the order of 50-70 k bytes and execution times on the order of 3-5 minutes for major calibration-simulation runs.

BASIC MATHEMATICAL APPROACH:

The basic mathematical relationship in the model is the conservation of mass within a river basin subarea:

$$(PPT + QSI + QGI) - (CET + QSO + QGO) = AS$$

where,
PPT = precipitation
QSI = total surface inflow
QGI = total groundwater inflow
CET = evapotranspiration
QSO = total surface outflow
QGO = total groundwater outflow
AS = change in system storage in snow, soil moisture, surface reservoirs, and groundwater.

The principal model variable is QSO. As a generally known quantity, the model simulations of QSO are compared with measured values. Calibration involves adjusting various time lag and simulation coefficients until the error in the predicted values of QSO is minimal. The minimization approach has been termed a pattern-search technique which is essentially a process of iteratively varying the parameters to achieve minimum variance.

GENERAL:

This model is one of the most recent in a long-term program of hydrologic modeling at Utah State University. Many of the earlier models or versions thereof have been incorporated or omitted from this model based on applications in a number of field situations. A listing is included in the reference by Huber, et al. (1976).

MODEL: A-9

REFERENCES:

Hillel, D. 1977. Computer Simulation of Soil-Water Dynamics. International Development Research Centre, Ottawa, Canada. pp. 155-198.

MODEL SCOPE:

Simulation is of the hydrology of a sloping agricultural field. Processes modeled include precipitation, infiltration, runoff, evaporation, redistribution, deep percolation, capillary rise from the water table, and groundwater drainage. Plant uptake and transpiration are not included. Output depicts the time and spatial distribution of water in the system.

INPUT REQUIREMENTS:

The geometry of the system is defined by stating the number of columns, number of layers per column, width of each column, and vertical dimensioning. Initial conditions such as saturated hydraulic conductivity and initial moisture distributions are detailed. The runoff hydraulic parameters are input, including roughness factors for the Manning's equation and surface slope. Boundary conditions are defined to depict the potential evaporation rate, water table elevation at its outflow to the drain and rainfall inputs. As in other unsaturated soil models, the relationships between water content, hydraulic conductivity, and suction must be known.

TIME AND SPATIAL SCALES:

The scale is a two-dimensional evaluation of a field sized system extending vertically to an impervious layer. The principal event is the period immediately preceding and shortly after a rainfall (until equilibrium conditions occur).

COMPUTER CODE STRUCTURE:

CSMP

BASIC MATHEMATICAL APPROACH:

Water added to the soil surface is divided into infiltration, surface storage and runoff. Infiltration is calculated by dividing the vertical unsaturated soil profile into layers and then routing flows through it using an iterative computation of contents, gradients, rates, and new contents. Runoff is handled by dividing the field into a number of vertical columns and then routing the surface water down slope with a successive kinematic wave equation. At the bottom of the slope the time distributed runoff is yielded by the last computations. In each column, the infiltration crossing the last compartment in the unsaturated zone is the inflow to the groundwater basin. A water table height increase is distributed through each column and then the saturated soil properties along with hydraulic gradients are used to calculate a lateral groundwater flow for the bottom of the slope.

GENERAL:

No field verification is presented. Code is listed in cited reference.

MODEL: A-10

REFERENCES:

Makkink, G. F. and H. D. J. Van Heemst. 1975. Simulation of the water balance of arable land and pastures. Centre for Agricultural Publishing and Documentation, Wageningen, The Netherlands. 79 pp.

MODEL SCOPE:

Simulation is of water movement and storage in a cropped field and the saturated-unsaturated soil beneath. The processes modeled include snow precipitation and melt, canopy interception and evaporation, soil surface evaporation and infiltration, unsaturated and saturated flow, evapotranspiration, micellar flow and plant withdrawal and hydration-dehydration. Output involves the time and spatial distribution of water in the system.

INPUT REQUIREMENTS:

The data listed as required input include the date of the last balance period and the current date, global and extraterrestrial solar radiation, a "place factor", air and dew point temperatures, relative humidity, wind speed, crop height, and depth of root zone, all for each day of the analysis. However, a number of data not listed as input are required nevertheless. For instance, the conductivity and moisture versus suction relationship, initial conditions, infiltration, and soil and crop characteristics are internal to the program as DATA statements.

SPATIAL AND TIME SCALES:

The analysis is of a large crop area, but the evaluation is made at one vertical "average" location. Time increments of 0.2 days are used in the calculation with output based on daily intervals. Model is one-dimensional and steady-state.

COMPUTER CODE STRUCTURE:

Code is written in Fortran IV for the CDC series computers. A main program with common linked subroutines and functions comprise the basic code structure. Although neither core nor time requirements are discussed, they are obviously small enough for most computers.

BASIC MATHEMATICAL APPROACH:

The plant-soil system is divided into "compartments" representing the various forms of moisture storage in the system. The computational system involves an iterative evaluation of compartment storage, the rate of moisture movement between compartments, and the calculation of contents (CONTENT at time t = CONTENT at time t-1 + RATE times Delta Time). The storage compartments include snow (existing as solid precipitation or heavy frost and flowing in the system by evaporation and melting), adhering water which stems from canopy interception (this moisture evaporates, drops into pools, or drops onto and infiltrates unsaturated soil). Pools filled with precipitation at rates greater than the saturated hydraulic conductivity of the soil (released from pools by evaporation and infiltration), the unsaturated soil profile (transmitting water to the saturated zone below or to the atmosphere above through transpiration and evaporation), the saturated zone (venting to transpiration, groundwater flow, water table storage changes, and flow to the unsaturated region through capillary use) and micellar water taken up by and stored in the clay structure. Subsets of the mass balance in the unsaturated zone are developed for the upper soil profile contributing to evaporation and the region of plant uptake. There are also storage balances for the moisture stored above and below 16 atm and field capacity, respectively. The basic rate processes are evapotranspiration and soil moisture redistribution. Evaporation and transpiration are computed with modified forms of the Penman equation. Unsaturated flow occurs when the soil moisture level exceeds field capacity.

GENERAL:

Although this model has many aspects of a general nature, its existing format is entirely site specific to the case studies it was validated against. To apply this model to other situations, much more data are needed. The code is presented in the reference cited above.

MODEL: A-11

REFERENCES:

Margheim, G.A., 1967. Predicting the quality of irrigation return flows. Unpublished M.S. Thesis, Civil Engineering Department, Colorado State University, Fort Collins, Colorado, December. 57 pp.

MODEL SCOPE:

Simulation is of the salinity constituents in flows entering the groundwater basin under irrigated croplands. Parameters include the concentrations of Ca^{++}, Mg^{++}, Na^{+}, and $SO_4^{=}$ in the flows entering the water table from deep percolation. The computer code does not contain an input dump or a printing of intermediate results, but does contain partial error flags for iteration limitations.

INPUT PARAMETERS:

No control parameters are utilized. Input data include the irrigation water concentrations of Ca^{++}, Mg^{++}, Na^{+}, Cl^{-}, and $SO_4^{=}$, and the concentrations of exchangeable Na^{+}, Ca^{++} and Mg^{++} in the soil. Input also requires concentrations of soluble Mg^{++}, Na^{+}, Ca^{++}, and $SO_4^{=}$ in the soil, solubility product of gypsum, and cation exchange constants for homovalent and monovalent-divalent exchange equations.

SPATIAL AND TIME SCALES:

Analyses are at a single or representative site in an irrigated field (accomplished by assuming uniform irrigation water applications). Steady-state moisture flux is assumed so time scale is set by user. However, an irrigation interval is generally selected.

COMPUTER CODE STRUCTURE:

Internal program linkage is facilitated by subroutines with data and results transferred through call statements. Program can be easily adapted to other computer systems since tape and disc functions are not performed. Core requirements are less than 40 k bytes while execution times are not known (probably 10-15 seconds per run). Model is programmed for CDC 6400 using Fortran IV language.

BASIC MATHEMATICAL APPROACH:

Under assumptions that gypsum is the only slightly soluble salt present in the soil system, the model first computes the ion concentrations in water percolating below the root zone and then the concentration of water intercepted by a drainage system. Effects of evapotranspiration are not directly considered in the soil chemistry phase. Computations in the soil chemistry phase involve the following iterative procedures controlled by iteration to iteration changes in calcium concentrations. A volume of irrigation water equal to the stored soil moisture volume in equilibrated with the soil-$CaSO_4$ system using the Gapon equation for exchange processes, and the Debye-Huckel gypsum solubility relations for solution equilibrium. The iterative procedure is repeated once the successive approximation procedure has converged for other volumes of irrigation water until the desired leaching is accomplished. Then, using a drainage equation developed by R.E. Glover, the volume of return flow is computed. The model assumes groundwater quality is poorer than deep percolation and mixing does not occur. An interface is thereby formulated from which the relative displacement is determined to arrive at the outflow mixture.

GENERAL:

Code is available in reference cited above. However, code is not documented nor verified against field data.

MODEL: A-12

REFERENCES:

Childs, S. W., and R. S. Hanks. 1975. Model of soil salinity effects on crop growth. Soil Sci. Soc. Amer. Proc., 39:617-622.

Melamed, J. D., R. J. Hanks, and L. S. Willardson. 1977. Model of salt flow in soil with a source-sink term. Soil Sci. Soc. Amer. Proc., 41:29-33.

Nimah, M. D., and R. J. Hanks. 1973. Model for estimating soil water, plant, and atmospheric interrelations: I. Description and Sensitivity, and II. Field test of model. Soil Sci. Soc. Amer. Proc., 37:522-527 and 37:528-532.

MODEL SCOPE:

The model described here is actually the result of several individual models. Nimah and Hanks (1973) added a plant root extraction system to an earlier one-dimensional moisture flow model. Childs and Hanks (1975) modified the Nimah and Hanks (1973) model for crop growth, salt flow, and irrigation uniformity. Then, the "Dutt Model" described herein by Dutt et al. (1972) and a simple source-sink model to account for chemical reactions were added. The simpler salt system was added to the water model by Melamed et al. (1977). Because the more complex Dutt model is described elsewhere, the version will not be detailed here.

The model simulates the one-dimensional flow of water in the transient, unsaturated soil profile including the spatial distribution of root uptake in response to surface evapotranspiration demand. Salts added to the system in the irrigation water or that exist in the solid form in the soil structure are transported through the system to the groundwater below. Dissolution and precipitation of salts in the root zone are simulated as a source-sink process rather than by chemical equilibrium. Ionic exchange and biological transformations are neglected. Output describes the spatial and time distributed water-salt system including evapotranspiration.

INPUT REQUIREMENTS:

The primary data necessary for the soil moisture flux are the hydraulic conductivity-water content and pressure head-water content relations, air dry and saturated moisture contents, root-water potential below which wilting occurs, depth distributed root distribution, initial moisture distribution, potential evapotranspiration at the surface and water inputs (irrigation or rainfall), osmotic potential of the irrigation water and of soil (depth distributed), the presence of a lower boundary water table, and crop cover. The salinity simulation requires the electrical conductivity of the irrigation water and solid soil salts, diffusion and dispersion coefficients, and initial solute distribution (electrical conductivity).

TIME AND SPATIAL SCALES:

The model is a one-dimensional analysis of the root-zone. Time scales vary in length from an irrigation interval to several years.

COMPUTER CODE STRUCTURE:

Programs are written in Fortran IV with common and call data transfer to subroutines. Execution time depends on the length of the real time simulation. Core requirements appear moderate (50-70 k bytes).

BASIC MATHEMATICAL APPROACH:

The model involves a moisture flow simulation, a salt transport system, and a simulation of the dissolution-precipitation processes (source-sink term). The moisture flow equation is the moisture content form of the unsteady flow equation developed by writing Darcy's Law and mass conservation equations in one dimension. This primary flow equation is modified by the inclusion of a root extraction term and solved with a implicit finite difference technique. The essential features of the root extraction term are described by Nimah and Hanks (1973). (See also the model of Feddes and Zaraday, 1977.) Flow to the roots is based on the difference between the root potential plus root resistance and the combined soil-water and osmotic potentials. This value is then multiplied by the hydraulic conductivity and a depth distributed rooting pattern. The root potential is determined by maximizing transpiration as was the case in the model by Feddes and Zaraday (1977) (which was based on this model).

The solute transport relationships are based on the equation of Bresler (1973) which includes diffusion and hydrodynamic dispersion. This equation is solved using a tridiagonal matrix solution of a Crank-Nicolson finite difference method.

The source-sink term accounting for precipitation and dissolution of salts is an on-off linear equation based on the difference the salinity concentration of the soil solution and a value at which precipitation will occur. The equilibrium concentration must be evaluated in the field.

GENERAL:

The model which has been calibrated against field data shows good predictive agreement with observed field data once calibrated. The code should be requested from its authors.

MODEL: A-13

REFERENCES:

Oster, J. D., and B. L. McNeal. 1971. Computation of soil solution composition variation with water content for desaturated soils. Soil Sci. Soc. Amer. Proc., 35:436-442.

Oster, J. D., and J. D. Rhoades. 1975. Calculated drainage water compositions and salt burdens resulting from irrigation with river waters in the western United States. J. Environ. Qual., 4:73-79.

MODEL SCOPE:

This simulation involves the salinity composition of root-zone drainage flows. Parameters include dissociated ionic species, gypsum and lime dissolution/precipitation, SAR, CO_2 partial pressure at bottom of root-zone (Pco_2), pH, EC, TDS, ionic strength, activities, and activity coefficients. Output also includes $CO_3^=$ and HCO_3^- ion pairing, and 1st and 2nd dissociation constants for carbonic acid. The computer code features an input dump, error flags for iterative sections, but no intermediate results.

INPUT REQUIREMENTS:

Control parameters are provided so a user may include magnesite (not fully developed) and forced saturation of soil lime. Up to 100 individual analyses can be run without dimension and common modification. Data include an identification of the test, Pco_2 at lower root-zone boundary, pH, Na^+, Mg^{++}, Ca^{++}, K^+, HCO_3^-, Cl^-, and $SO_4^=$ in applied irrigation water, and the estimated leaching fraction.

SPATIAL AND TIME SCALES:

Simulation is of a single or representative site in an irrigated field. Analysis is steady-state and encompasses the drainage period of the irrigation interval. Model is one dimensional.

COMPUTER CODE STRUCTURE:

Internal program linkage is accomplished by subroutine and functions with common data transfer. The program can be easily adapted, all or in part, to other computer systems or programs. Approximate core and execution time requirements are 70 k bytes and 10-15 central processor seconds, respectively. Programmed originally for an IBM 360 computer using a Fortran IV language.

BASIC MATHEMATICAL APPROACH:

The basic modeling approach along with important assumptions, supportive literature, and data requirements is well described in the previously cited references. The interested user is therefore referred directly to these sources for more detailed information. In general terms, the computations begin by pre-concentrating the ions in the irrigation water by dividing each by the leaching fraction. Then an iterative procedure (governed by convergence tolerances on ionic charge balance, changes in ionic concentrations for Ca and CO_3, and dissociation constants) is used to compute the salinity constituents in the drainage. The extended form of the Debye-Huckel equation is utilized to calculate activity coefficients in the equilibria analyses. Gypsum and lime precipitation/dissolution is used to achieve convergence. Leachate pH is governed by the soil lime equilibria and cation exchange is not included.

GENERAL:

The computer code is available from the authors cited above. Documentation within the code is excellent and substantial verification trials are reported to demonstrate the utility and limitations of the model.

MODEL: A-14

REFERENCES:

Rai, D., and W.T. Franklin, 1973. Program for computing equilibrium solution composition in $CaCO_3$ and $CaSO_4$ systems from irrigation water compositions. Water Management Technical Report No. 29. Colorado State University, Fort Collins, Colorado. October. 42 pp.

MODEL SCOPE:

Simulation is of the salinity composition of root-zone drainage. Parameters include dissociated ionic species, gypsum and lime dissolution - precipitation, SAR, pH, EC, TDS, ionic strength, activity, and activity coefficients. Output includes $CO_3^=$, HCO_3^-, and $SO_4^=$ ion pairing with Ca^{++}, Mg^{++}, K^+, and Na^+. The computer code features an input dump, error flags for iterative sections, but no intermediate results.

INPUT REQUIREMENTS:

The program does not include any control options. Input data are sample identification, total concentrations of Ca^{++}, Mg^{++}, Na^{+}, K^{+}, HCO_3^{-}, $SO_4^{=}$, and Cl^{-} in the irrigation water, CO_2 partial pressure, and the leaching fraction. Units are in equivalents per liter except for CO_2 (atm) and leaching fraction (expressed as a fraction). Program operates on one sample during each run.

SPATIAL AND TIME SCALES:

The simulation involves a single or average condition in an irrigated field on a one-dimensional basis and steady-state system is assumed.

COMPUTER CODE STRUCTURE:

The code consists of only a main program in the latest version, although the program in reference cited above contained a subroutine for solution of cubic roots. The program can be easily modified for use on computers other than the CDC 6400 at Colorado State University. Core requirements are approximately 30 k bytes. Execution time per run is 15-70 central processor seconds. Code language is Fortran IV.

BASIC MATHEMATICAL APPROACH:

The basic modeling approach, along with pertinent assumptions and simplifications, is well documented in Rai and Franklin (1973). Program is now revised to include nesquehonite. Computations begin by preconcentrating ionic concentrations in the irrigation water by dividing each by the leaching fraction. Ionic strength and activity coefficients are initially calculated by assuming no pairing. Then, a three-dimensional successive approximation loop is entered in which calcium equilibrium is used to arrive at leaching water chemistry. The primary loop flow involves (1) computation of free anions; (2) calculation of free cations; (3) calculation of charged ion pairs; (4) calculation of ionic strength; and (5) calculation of activity coefficients. Then, lime or gypsum equilibrium is checked. If solution is in equilibrium, the program goes to next calcium system or concludes. If nonequilibrium exists, approximations resume at beginning of loop. The Debye-Huckel equation is used for activity coefficients and literature references for equilibria constants are used for the calcium system. Cation exchange is not included.

GENERAL:

The code is available from the authors cited above. Code is moderately documented itself whereas the reference is extensive. Model has been verified against literature and field data. This program is also available for an HP 9825 programmable calculator from the writer.

MODEL: A-15

REFERENCES:

Saxton, K.E., G.E. Schuman, and R.E. Burwell. 1977. Modeling nitrate movement and dissipation in fertilized soils. Soil Sci. Soc. Amer. Proc., 41:265-271.

MODEL SCOPE:

Simulation is of the nitrate-nitrogen-occurrence, movement, and dissipation in 1-2 meters of the unsaturated zone under fertilized agricultural lands. Processes included in the model are solute transport (infiltration, redistribution, and percolation), crop uptake, disposition of added fertilizer, rainfall additions, mineralization and nitrification. Denitrification, fixation, and runoff losses were assumed negligible. Other nitrogen processes were considered negligible. The moisture flow requirements must be input to the model and must include soil evaporation, plant adsorption from each 15-cm layer, infiltration, soil-moisture redistribution between layers, and soil-moisture in each layer.

INPUT REQUIREMENTS:

Water flow data for this model comes from the model described by Saxton, et al. (1974). Output from that model or similar daily values for uptake by soil segment, infiltration, soil moisture storage volumes, and deep percolation must be incorporated. Then, the time distributed data describing nitrogen additions to the system, total and depth distributed plant uptake of nitrogen, and the initial nitrogen profile in the soil are read.

TIME AND SPATIAL SCALES:

Daily calculations are made of a one year event in a one-dimensional, transient, unsaturated zone.

COMPUTER CODE STRUCTURE:

Using a main program to read tape output from the soil-moisture model, the general nutrient calculations are carried out in subroutines using common and call statement data transfer. Execution times for the Fortran Code are on the order of 10-20 seconds. Core requirements should not exceed 50-60 k bytes.

BASIC MATHEMATICAL APPROACH:

Nitrogen transport is based on the assumption that within each 15-cm soil segment, the concentrations of nitrate are uniformly distributed. Thus, nitrates leaving or entering a layer are calculated as the product of the moisture movement and the existing nitrate concentrations. New concentrations are computed for each hour and soil layer to aggregate the transient system on a daily basis. The withdrawal of nitrates from the soil layers is assumed proportional to water absorption. An annual uptake figure is distributed on a daily basis assuming a proportionality with dry matter production and then distributed in the soil profile according to root distributions. Nitrogen added to the upper soil layers in precipitation or fertilizer moves as indicated above, but ammonium fertilizers are assumed to be either adsorbed or converted to nitrate. A first-order temperature dependent decay function was used to describe the ammonium conversion to nitrate. A 10% loss due to volatilization was assumed on initial application. Mineralization is fixed at 52 kg/ha per year within the upper soil layer and is distributed with time proportionally to the temperature in the soil between May and September.

The calculation proceeded in the following sequence: fertilizer addition, mineralization addition, uptake, infiltration addition and transport, and transport by redistribution and percolation. A revised nitrate profile is calculated after each process and printed at the day's end.

GENERAL:

The model has been verified (with good agreement) with field data from two watersheds. This is a readily usable model only if the moisture flow is supplied by the earlier model. Thus, modifications should be made to operate this one independently for widespread application. Computer codes must be requested from the authors of the cited references.

MODEL: A-16

REFERENCES:

Tanji, K. K., L. D. Doneen, G. V. Ferry, and R. S. Ayars. 1972. Computer simulation analysis on reclamation of salt-affected soils in San Joaquin Valley, California. Soil Sci. Soc. Amer. Proc. 36:127-133.

MODEL SCOPE:

Simulation is of the interaction of soluble salts (Ca^{++}, Mg^{++}, Na^{+}, K^{+}, $SO_4^{=}$, Cl^{-}, HCO_3^{-}, and NO_3^{-}) and Boron in a soil profile. The model was developed to describe leaching processes so the output includes drainage water quality, soil profile chemistry (changes in soluble, and adsorbed salts). It also predicts the depth of leaching water required to achieve specific values of soluble salts, boron, and exchangeable sodium concentrations in the soil profile. Output includes ionic strengths, activity coefficients, ion pairs, stoichiometric solute concentrations (dissociated and undissociated), total soluble cations, SAR, and ESP.

INPUT REQUIREMENTS:

Input data include leaching water salinity composition, initial soil profile salt distribution, depth distributed exchangeable Ca^{++}, Mg^{++}, and Na^{+}, cation exchange constants, gypsum content, adsorbed boron, Langmeier constants, and moisture contents at saturation and field capacity.

TIME AND SPATIAL SCALES:

The principal time frame is the period covered by an application of irrigation water and the subsequent leaching. The model is one-dimensional and encompasses the unsaturated zone of depth specified by the user.

COMPUTER CODE STRUCTURE:

The program is a Fortran code without subroutines or user supplied functions. Core and execution times are not given but appear small (40-60 k bytes, and about 1-2 minutes).

BASIC MATHEMATICAL APPROACH:

The soil profile is divided into layers with moisture movement between layers when field capacity is exceeded. A chromatographic approach to salt transport between layers is assumed. Solute from one layer moves into a lower layer, mixes with the resident solution (at equilibrium) and equilibrates.

The calculation of the equilibrium chemistry for the salts utilize the Guggenheim-Davis equation for activity coefficients and experimental solubility and dissociation coefficients. Boron adsorption-desorption is simulated with a Langmeier isotherm.

GENERAL:

Model was verified with field data and has served as a starting point for several steady-state models developed to predict the chemistry of leaching water. Code must be requested from authors cited above.

MODEL: A-17

REFERENCES:

Dutt, S.R., M.S. Shaffer, and W.S. Moore, 1972. Computer simulation model of dynamic bio-physicochemical processes in soils. Technical Bulletin 196, Agricultural Experiment Station, University of Arizona, Tucson, Arizona. October. 101 pp.

Shaffer, M.S., R.W. Ribbens, and C.W. Huntley. 1977. Prediction of mineral quality of irrigation return flow, Volume V. Detailed return flow salinity and nutrient simulation model. EPA-600/2-77-179e. Robert S. Kerr Environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Ada, Oklahoma. August. 228 pp.

MODEL SCOPE:

This model simulates chemical and physical processes associated with agricultural lands drained by subsurface drainage systems. Basic input data involves the field application of irrigation or precipitation with associated salts and nitrogen nutrients. Model output is the prediction of drainage quality with evaluations at intermediate points in the plant-soil-aquifer system. Program includes intermediate output and various error flags.

INPUT DATA:

This is a very large computer model well documented by Shaffer, et al. (1977). As a consequence, the input requirements are elaborate. The following input data summary is given by Shaffer, et al., (1977):

(1) Drainage parameters: drain spacing and depth, depth to impermeable barrier, envelope size, saturated hydraulic conductivity, porosity, and specific yield or storage coefficients;

(2) Unsaturated flow parameters: the hydraulic conductivity versus moisture content function, and pressure head versus moisture content relations;

(3) Soil chemistry data: meq/l of Ca^{++}, Mg^{++}, Na^{+}, $CO_3^{=}$, HCO_3^{-}, Cl^{-}, $SO_4^{=}$, NH_4^{+}, NO_3^{-}, and urea in soil extract, pH, cation exchange capacity, gypsum content, presence of lime, bulk density, organic nitrogen, carbon-nitrogen ratio, and the nitrifier population-salt response relationship;

(4) Crop information: rooting depth and distributions, evapotranspiration rates as read in or calculated using an irrigation scheduling program, and plant uptake of nitrogen;

(5) Water application data: irrigation schedules and amounts (or precipitation amounts and timing) and an effective precipitation relationship;

(6) Fertilizer data: fertilization schedules, amounts of NO_3^{-}, NH_4^{+}, Urea, Ca^{++}, $SO_4^{=}$, and $CO_3^{=}$, application depth and organic nitrogen plowed in with corresponding C-N ratio, and application ratio;

(7) Irrigation water analyses: concentrations of NH_4^{+}, NO_3^{-}, Ca^{++}, Na^{+}, Mg^{++}, HCO_3^{-}, $CO_3^{=}$, Cl^{-}, and $SO_4^{=}$; and

(8) Miscellaneous soils data: soil temperature and coefficients relating to nitrification and denitrification.

SPATIAL AND TIME SCALE:

The spatial scale is a two-dimensional evaluation of the vertical region from the soil surface to the drainage system. Time scales are mixed depending on the calculation being made. Time varies from fractions of a day to an irrigation interval and even up to an irrigation season. The model is transient in nature.

COMPUTER CODE STRUCTURE:

The primary code structure is in a main program-subroutine format utilizing common, call, and tape file data transfer. The size of this model requires extensive use of overlay systems if the entire package is used. Consequently, core requirements are only 140-150 k bytes at any instant. Time for execution varies from one to two minutes up to several minutes depending on the scope of the job. Although the basic program language is Fortran IV, this model is not easily adapted in its entirety. Except for some planning use by the Bureau of Reclamation, this is primarily a research tool and not applicable by most planning groups.

BASIC MATHEMATICAL APPROACH:

This model is composed of individual models which extend across several disciplines. Consequently, there is more likely to be more interest in the various submodels rather than the total package. The program is linked together with detailed overlay systems and numerous by-pass options provide substantial flexibility. The interested user can find excellent explanatory comments in the references noted above. However, to identify the model's basic characteristics, this section will be divided by major submodels.

Irrigation scheduling. Unlike the irrigation scheduling program available to schedule and update irrigations, this model predicts irrigation schedules and amounts using historical data exclusively. Based on geographical data, solar radiation, and temperature, the program first computes potential evapotranspiration for alfalfa using the Jensen-Haise equation. Adjustments are made for seven other crops using standard growth stage coefficients. Then, a simple mass balance of the root zone is developed. Soil moisture is allowed to be depleted to an "allowable moisture depletion" before an irrigation is scheduled. Coefficients for various irrigation efficiency and losses produce deep percolation and surface runoff estimates. The output from the model is recorded on cards punched for subsequent use in the unsaturated moisture-chemistry models (infiltration) and the drainage calculation (deep percolation).

Soil moisture movement. The unsaturated flow submodel is a finite difference simulation of the transient moisture flow equation in one dimension. Hydraulic conductivity is taken as a function of moisture content as is pressure head. Simulation includes infiltration, redistribution, drainage, and plant uptake. Plant uptake is determined from information of total uptake which is distributed throughout the soil profile in proportion to an average root distribution.

Unsaturated soil chemistry. The complex soil-water system is simulated from a chemical-biological standpoint by a group of subroutines designated as the unsaturated chemistry program. The program has two primary components: (1) simulation of the soil nitrogen system; and (2) the soil salinity series. This model is the basic programming package reported by Dutt, et al. (1972).

The nitrogen phase of the program considers urea hydrolysis, nitrification of NH_4^+-N, net mineralization-immobilization of both organic-N and NH_4^+-N, immobilization of NO_3^--N, plant uptake of NH_4^+-N and NO_3^--N, and denitrification. In addition, the NH_4^+-N reaction in the cation exchange system is considered. With the exception of the cation exchange process, the nitrogen simulation assumes a first-order kinetic approach using regression functions for the transformation rates. Denitrification is evaluated using zero-order kinetics. Nitrogen uptake may be evaluated by either of two methods. First, the user may specify total N uptake and root distribution which yield the plant N uptake in each soil segment per unit of time. In this case, the user specifies the fractions of NO_3^-, and NH_4^+ uptake. The second assumes uptake is proportional to water uptake. Output from these segments of the model predicts mass distribution of the various nitrogen components.

The salinity phase of the models evaluates ion exchange, solution-precipitation of gypsum and lime, formation of undissociated ion pairs, and transport of the soluble species (Ca^{++}, Mg^{++}, Cl^-, Na^+, etc.). Because these various reactions occur quickly, solution equilibria are used to describe the segments of the salinity system. The ion exchange and solution-dissolution of the slightly soluble salts are computed using standard approaches such as the Gibbs phase rule, Debye-Huckel theory, and Gapon equations. An iterative successive approximation procedure is used to determine the chemistry within the soil profile and in the deep percolation. The procedure involves (1) calculation of lime solubility; (2) calculation of gypsum solubility; (3) undissociated $CaSO_4$ and $MgSO_4$ ion pair reaction; (4) Na^+-Ca^{++}, Mg^{++}-Ca^{++}, and Na^+-NH_4^+ ion exchange; and (5) evaluation of $CaCO_3$ dissociation.

The movement and distribution of water is either read in or produced by the unsaturated flow program. For the soluble ions, a mixing cell concept is used to simulate solute dispersion and movement. This assumes complete mixing occurs in each soil-time increment and that molecular diffusion is negligible.

Drainage Model (Dynamic Equilibrium). Flow moving below the crop rootzone is routed to surface receiving waters via this drainage program. The model was designed to predict the response of a subsurface drainage system consisting of parallel, equally spaced tile drains, to deep percolation inputs. Principal outputs are the mid-space water table elevation and drain discharge. Deep percolation may be developed for the program through card read input or directly from the unsaturated flow model. The mathematical approach is the general Bureau of Reclamation drainage equations.

The water table shape is approximated as a fourth degree parabola which uses specific yield to compute instantaneous rises and declines in water table positions. Hooghoudt's equivalent depth is used to correct for near-drain convergence effects not treated by the Dupuit-Forchheimer assumptions. The Moody solutions are used to approximate these systems.

Drainage Model (steady-state). The general modeling system also includes a steady-state drainage system model based on potential theory to define stream tubes. An average deep percolation rate is computed from the values determined by the unsaturated flow program. A system of nodes is defined at which the infinite series mathematical solutions are computed. Under this approach, the flow velocities and travel times are estimated thereby yielding an estimate of the time required for a water volume to reach the drainage system. These data are determined for use in the saturated chemistry and drainage effluent chemistry parts of the program.

Saturated Chemistry Program. This program predicts the two-dimensional distribution of saturated flow chemistry below an irrigated field. The stream tube flows predicted by the steady-state drainage model along with chemical soil analysis serve as model input. Each stream tube is analyzed separately and is divided into segments of equal volumes. Flow is accumulated until it reaches the pore volume of a segment and then is moved by piston displacement. After each displacement, the solution is equilibrated with the solid and exchangeable phases. Lateral dispersion and diffusion are neglected since lateral and longitudinal mixing among stream tubes is not considered. Chemical transformations are identical to those in the unsaturated chemistry model except denitrification is simulated in the transition zone between unsaturated and saturated regions. The denitrification rate is assumed temperature dependent but not affected by substrate concentration. Above a "saturation level" the rates are assumed to be zero-order and below this level to be first-order. The aquifer profile is assumed to be homogeneous until the heterogeneous nature is computed through consideration of individual stream tubes.

Drain Effluent Prediction. This program takes the flow rates from the steady-state drainage analysis and its corresponding chemistry and aggregates each stream tube into a monthly drainage discharge. The salt load from the drainage system is thus determined by mixing and routing the flows in each stream tube.

GENERAL:

This modeling system is well documented, verified in field conditions, and available for broad use. However, the system itself is far larger than required by most research groups and far too complex for use by planning groups. Many possible uses can be made using individual segments listed above. Computer and data requirements are substantial. The modeling system is probably the largest, most exhaustive available as an integrated package. Code listings are available from the Bureau of Reclamation.

MODEL: A-18

REFERENCES:

Walker, W.R. 1970. Hydro-salinity model of the Grand Valley. M.S. Thesis, Civil Engineering Department, CET-71WRW8. Colorado State University, Fort Collins, Colorado. August. 94 pp.

MODEL SCOPE:

This simulation is limited to the hydrologic and salinity systems in an irrigated valley. Diversions from reservoirs, rivers, tributary inflows, or groundwater are routed through the agricultural system. Surface as well as subsurface flows and flow qualities are predicted along with consumptive use.

INPUT REQUIREMENTS:

Input data consist of mean monthly values for temperature, percent daylight hours, Blaney-Criddle climatic coefficients, areas of each land use, Blaney-Criddle crop growth stage coefficients, river inflows, tributary inflows, river outflows, lateral diversions, surface drainage outflows, drainage base flows, soil moisture storage capacities, root-zone diversions, exports, imports, water table fluctuations, precipitation, and equilibrium salinity concentrations of each of these flows. A series of groundwater data are also required. These include the number of strata at the groundwater basin's return flow point, and the number of normal locations where the gradient in each of these strata is defined. At the outflow point or close by, an initial value of hydraulic conductivity and cross-sectional area is required.

SPATIAL AND TIME SCALES:

The scale of the model is a macroscopic simulation of an irrigated area and the hydrology immediately surrounding it. A time resolution of one month is taken. Analysis is steady-state.

COMPUTER CODE STRUCTURE:

The computer code consists of a main program and subroutine served by both common and call statement data transfer. Written in Fortran IV, it should be adaptable in most computers. Core requirements are approximately 43 k bytes and time needs are about 25-30 central processor seconds per run.

BASIC MATHEMATICAL APPROACH:

A mass balance is made of the water flow system and the salt system is attached by multiplying by the concentrations associated with each segment of the system. Flows entering the main conveyance are segregated into seepage by a conveyance efficiency, lateral diversions as input, and operational wastes by difference. Lateral diversions are likewise delineated into seepage, root-zone diversions, and tailwater. Finally, root-zone diversions are allocated to root-zone storage, deep percolation or consumptive use. Summing the surface and subsurface flows from each breakdown yields an estimate of the respective return flows. At this point an estimate of the groundwater return flows is made on the basis of a groundwater model. A comparison of the mass balance and groundwater model estimates of subsurface return flows is made in a manner which calculates an adjusted aquifer hydraulic conductivity by month. The model is then systematically adjusted until the values of hydraulic conductivity are homogeneous. When the water system is satisfactorily modeled, the salinity system is added.

GENERAL:

The model is a second or third generation modeling concept initiated at Utah State University. Consequently, these early models will not be described; however, this model is an approach that can be applied with generally available data. The evapotranspiration and root zone analysis needs updating. Application has been made with good accuracy in the Grand Valley of western Colorado.

APPENDIX B

REFERENCES REQUIRED FOR IRRIGATION RETURN FLOW STUDIES

This appendix is included to provide a list of references which should be obtained for all Irrigation Return Flow studies. This list is not intended to be complete, but will perhaps provide a minimum basic reference library for persons working in this area.

BASIC REFERENCES

Hagan, R.M., H.R. Haise and T.W. Edminister (eds.), Irrigation of Agricultural Lands. American Society of Agronomy, Monograph No. 11.

Kovda, V.A., D. Van Den Berg, R.M. Hagan, editors. 1973. Irrigation Drainage and Salinity. FAO/UNESCO, an International Source Book. Hutchinson & Co., Ltd., London.

Skogerboe, G.V. and J.P. Law, Jr. 1971. Research Needs for Irrigation Return Flow Quality Control. 13030-11/71. Water Pollution Control Research Series. United States Environmental Protection Agency, Office of Research and Monitoring, Washington, D.C. November.

Utah State University Foundation, 1969. Characteristics and Pollution Problems of Irrigation Return Flow. Robert S. Kerr Research Center, Ada, Oklahoma. May. 237 p.

van Schilfgaarde, J. (ed.), 1974. Drainage for Agriculture. Agronomy Monograph No. 17. American Society of Agronomy. Madison, Wisconsin. pp. 433-463.

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Doorenbos, J. 1976. Agro-meteorological Field Stations. Irrigation and Drainage Paper No. 27. Food and Agriculture Organization of the United Nations. Rome. 94 pp.

Doorenbos, J. and W.O. Pruitt. 1977. Crop Water Requirements (Revised Edition). FAO Irrigation and Drainage Paper 24, Food and Agricultural Organization of the United Nations, Rome, Italy.

Jensen, M.E. (ed.), 1973. Consumptive Use of Water and Irrigation Water Requirements. ASCE, New York, New York.

Jensen, M.E. 1975. Scientific Irrigation Scheduling for Salinity Control of Irrigation Return Flows. EPA-600/2-75-064. U.S. Environmental Protection Agency, Ada, Oklahoma, November.

Kincaid, D.C., and D.F. Heerman. 1974. Scheduling Irrigations Using a Programmable Calculator. ARS-NC-12. Agricultural Research Service, U.S. Department of Agriculture. February.

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Bos, M.G. 1976. Discharge Measurement Structures, Publication No. 20. International Institute for Land Reclamation and Improvement/lLRl. P.O. Box 45, Wageningen, The Netherlands.

Skogerboe, G.V., R.S. Bennett, W.R. Walker, 1973. Selection and Installation of Cutthroat Flumes for Measuring Irrigation and Drainage Water. Colorado State University Experiment Station. Technical Bulletin 120. Fort Collins, Colorado. December. 74 p.

Skogerboe, G.V., M.L. Hyatt, R.K. Anderson, and K.O. Eggleston. 1967. Design and Calibration of Submerged Open Channel Flow Measurement Structures. Part 3, Cutthroat Flume. Utah Water Research Laboratory, Report WG31-4. Utah State University, Logan, Utah. April.

Skogerboe, G.V., M.L. Hyatt, and L.H. Austin. 1967. Design and Calibration of Submerged Open Channel Flow Measurement Structures. Part 4, Weirs. Utah Water Research Laboratory, Report WG31-5. Utah State University, Logan, Utah. May.

Skogerboe, G.V., M.L. Hyatt, and K.O. Eggleston. 1967. Design and Calibration of Submerged Open Channel Flow Measurement Structures. Part 1, Submerged Flow. Utah Water Research Laboratory, Report WG31-2. Utah State University, Logan, Utah. February.

Skogerboe, G.V., M.L. Hyatt, J.D. England, and J.R. Johnson. 1967. Design and Calibration of Submerged Open Channel Flow Measurement Structures. Part 2, Parshall Flumes. Utah Water Research Laboratory, Report WG31-3. Utah State University, Logan, Utah. March.

USDI, USBR. 1974. Water Measurement Manual. Second Edition. Denver, Colorado.

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APPENDIX C

CONVERSION FACTORS

Metric Units	English Units	English to metric (multiply x English Units) 1/
Length		
kilometer, km	mile, mi	1.609
meter, m	yard, yd	0.914
meter, m	foot, ft	0.3048
centimeter, cm	inches, in	2.54
centimeter, cm	feet, ft	30.5
millimeter, mm (precip. and evaporation)	inches, in	25.4
Area		
kilometer^2, km^2	mile^2, mi^2	2.590
kilometer^2, km^2	acre, ac	0.00405
hectare, ha	acre, ac	0.4046
meter^2, m^2	feet^2, ft^2	0.0929
meter^2, m^2	mile^2, mi^2	3.861 E-07
Volume		
meter^3, m^3	acre-inch, Ac-in	102.8
meter^3, m^3	acre-feet, AF	1233.6
meter^3, m^3	feet^3, ft^3	0.02832
meter^3, m^3	bushel (US), bu 2/	28.38
liter, ℓ	quart (liquid), qt	0.946

1/ To convert from metric to English units, divide the metric value by the value in the column.

2/ Bushels as a unit of weight will vary from crop to crop. Metric yields are expressed in kg/ha. The ASAE 1977 Yearbook has information on some crop weights per bushel.

Mass		
ton (metric)	ton (English)	0.9072
kilogram, kg	pound, lb	0.454
gram, gm	ounce (avdp), oz	28.35
Pressure (Force per unit area)		
bar	lb/inch^2, psi	0.06895
bar	atmosphere, atm	1.013
kg (weight)/cm^2	atmosphere, atm	1.033
kilopascal, KPa	lb/inch^2, psi	6.895
atmosphere, atm	lb/inch^2, psi	0.06805
millibars, mb	inches of mercury (20°C)	33.86
atmosphere, atm	feet of water (20°)	34.01

Metric Units	English Units	English to metric (multiply x English Units)
Water Measurement		
hectare-meters, ha-m	acre-feet, AF	0.1233
hectare-meters, ha-m	acre-inches, ac-in	0.01028
hectare meters/hectare	acre feet/acre	0.3047
meter^3/sec	feet^3/sec	0.02832
liter/sec	gallons/minute	0.0631
liters/sec	feet^3/sec	28.32
liters/sec	Colorado Miners Inch 3/	0.74
Sediment		
tons (m)/day	tons (E)/day	0.907
kg/m^3	ppm	depends on density
Temperature		
Celsius	Fahrenheit	5/9(°F-32) 4/

3/ Miners inches are established by State legislation and will vary from state to state.

4/ For Celsius to Fahrenheit use (9/5°C) + 32.

Miscellaneous conversions

one gallon (US gal)
= 231 in^3
= 0.13368 FT^3

gallon/minute (gpm)
= 0.00223 cfs
= 0.00442 AF/DAY

one cubic foot (FT^3)
= 1,728 in^3
= 7.481 gallons
= 62.4 lb (mass)

cubic feet/sec (cfs)
= 448.8 gpm
= 1.984 AF/day

one acre foot (AF)
= 43560 FT^3
= 325,851 gallons
= 1357 tons

acre foot/day
= 0.504 cfs
= 226.3 gpm

Chemical Quality to Tons of Salt

(PPM) x (AF) x (0.00136) = TONS (ENGLISH) TO SALT/UNIT TIME
(PPM) x (m^3/sec) x (0.0864) = TONS (METRIC)/DAY OF SALT